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A WARNING TO THE READER

There are so many books on popular astronomy that to add yet one more to their number requires some justification. The positive aim of the present book is to attempt to give an unvarnished straightforward account in simple terms of the sort of problems with which the ordinary working astronomer is concerned. It is, as far as possible, up to date, and aims at taking the reader to the frontiers of the subject where advances are now being made, or are likely to be made in the future. It is not concerned with any possible philosophical or theological implications which astronomy may have. It is not intended to be a comprehensive account of astronomy in all its aspects: for this the reader must consult one of the books listed in the appendices. It does not even claim to give a properly balanced treatment of all the newest advances, for naturally it lays most stress on those branches of astronomy in which the author is most interested. It does, however, do its best to be honest about this, and where it includes a personal 'notion' a label is usually attached bearing the legend 'To be taken with a pinch of salt.'

Many professional astronomers will probably say that the book makes too much out of the stars, and too little out of the nebulæ and the type of long-range observations which are possible with the new giant telescopes of the United States and South Africa. Planetary observers will complain that the account of the solar system is too compressed and that such objects as comets are passed over too lightly. Variable star observers will feel that to lump them together in a short chapter entitled 'Oddities' with all the other unusual stars is not good enough. Lastly, the account of the sun is far too sketchy and compressed.

These choices are deliberate. If we concentrate on stellar structure and neglect the farthest confines of the universe it is because astronomy in Britain cannot, for want of a suitable climate, match American observational practice; and also because a large share, possibly the major part of the theoretical

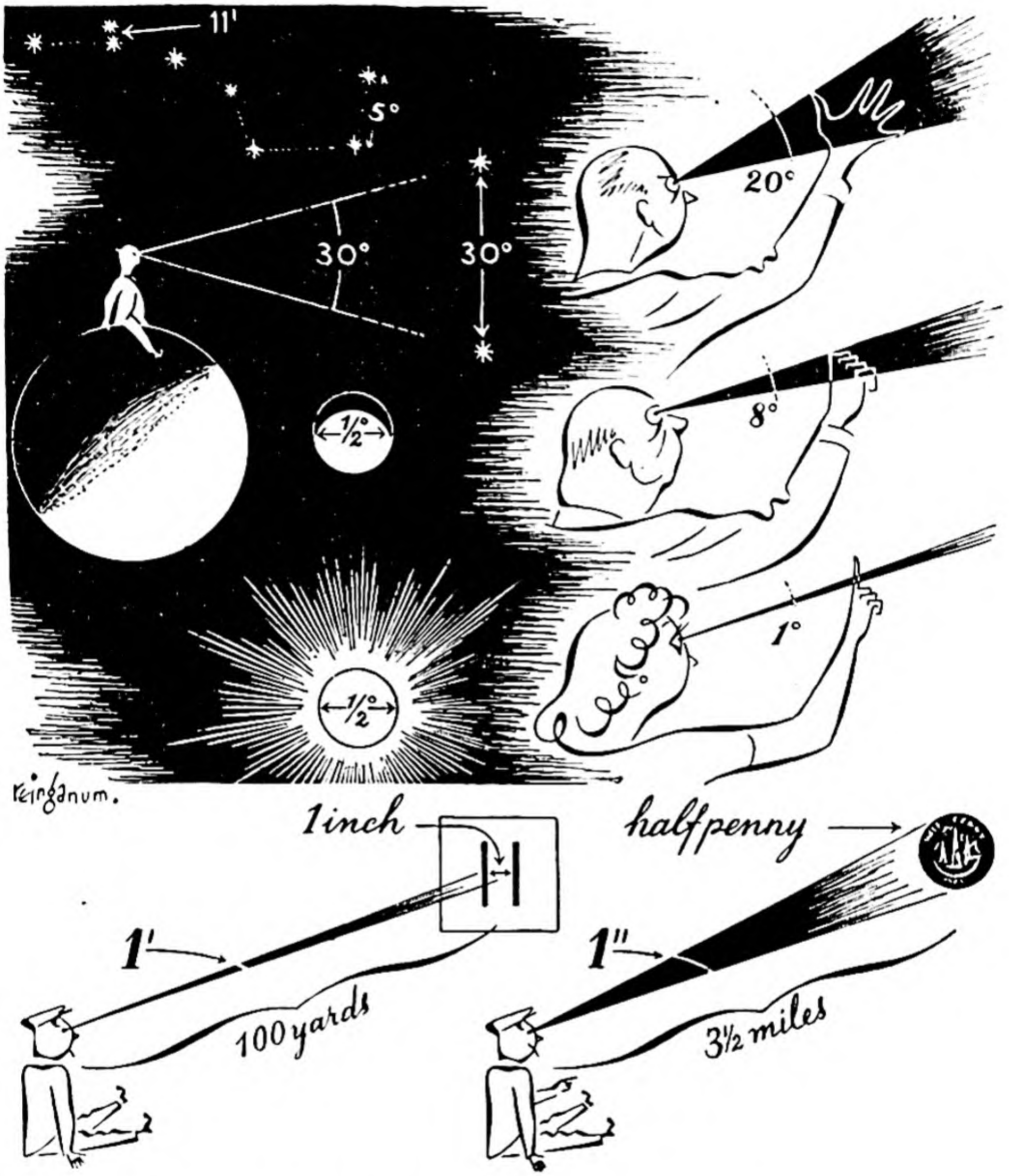
work on stellar structure, has been done in Britain. The reader interested in the feats of the big American telescopes can read about them in such admirable books as Hubble's Realm of the Nebulæ. *A little local patriotism in expounding the work of British astronomers is therefore not out of place.*

If the reader is interested in the detailed appearance of planéts he can find excellent accounts elsewhere. Local patriotism in this connection is a little out of place. We shall get a very distorted view of the structure of the universe if we concentrate on one of its rarest phenomena—our own planetary system.

The compression of the account of solar research is also deliberate, for it is a subject which would require a whole book to itself.

The present volume is offered as an approximation to the point of view of the working astronomer, and it is believed that if the reader were to overhear a discussion of the sort which often takes place in spare moments between research workers in the same observatory, he would have a good chance of finding something about it in this book.

Fig. 1



A NOTE ON ANGLES

IN this book we shall continually have to express numerical results in terms of angles. When we look at the sky we say, for instance, that the angular separation between the 'pointers' of the Plough is about 5°. By this we mean that the directions from our eye to these two stars are inclined to one another at an angle of 5°.

We shall use both larger and smaller angles than this. An angular distance of 90° *means that the directions to two stars are perpendicular to one another. If you hold your hand at arm's length with the fingers outstretched, the angular separation of the tips of your thumb and little finger is about* 20°. *Hold your clenched fist at arm's length. The angular diameter of the back of your hand across the knuckles is about* 8°. *Your first finger held up at arm's length is about a degree across.*

Each degree is divided into sixty parts called minutes and each minute into sixty seconds. These measure angles *and are called minutes and seconds of* arc, *being denoted by ′ and ″. These do not mean feet and inches although they are the same signs. Minutes and seconds of* time *are never denoted by these signs, but always by the abbreviations m. and s.*

The angular diameters of the sun and moon are each about half a degree, or 30′ (*thirty minutes of arc*). *The angular distance from the star Mizar, at the middle of the handle of the Plough, to its fainter companion, Alcor, is* 11′. *The smallest angle distinguishable with the naked eye is about* 1′ (*one minute of arc*), *i.e. if two bold black parallel lines are drawn on a sheet of white card at a distance of one inch apart, then they can just be seen as separate lines when the card is at a distance of* 100 *yards. A halfpenny is one inch across and has an angular diameter of* 1″ (*one second of arc*) *when held up at a distance of* 206,265 *inches, or about* 3¼ *miles away.*

Chapter One

SOME HISTORICAL HIGH-LIGHTS

IT is usual to begin the discussion of any subject by saying something about its history. This brief historical introduction is included not merely for form's sake, but in an attempt to show why astronomy developed at all, and why it has reached its present stage of evolution, when much of it seems infinitely remote from ordinary life.

The direct applications of astronomy are easy enough to understand. For example the time registered by ordinary clocks is based, in the end, on the time which it takes for the earth to turn once on its axis. This is the interval between the moments at which any place on the earth passes a fixed direction in space, and the nearest thing to a fixed direction which we know is the direction to a distant star. In this connection the fixed stars serve as markers of positions on the sky by which to judge the rotation of the earth, and they fulfil the same office for the navigator who uses them to determine his position on the sea or in the air.

Besides these obvious uses there are certain other contributions which astronomy has made to the material progress of civilization, some so simple and so closely interwoven with our daily lives that they are taken for granted. The most obvious is the calendar, which has existed in many forms of a greater or less accuracy, all of which have an astronomical basis. Without a calendar, agriculture was dangerously uncertain; the times of sowing and reaping could not be gauged in advance, nor, in ancient Egypt could the time of the Nile flood be predicted. So important was this knowledge in the ancient world that those who possessed it became priests or kings and their people prospered.

But even in ancient times astronomy had passed beyond the stage of meeting immediate practical needs. Men became interested in it for its own sake, and some remarkably accurate astronomical observations, whose contemporary practical value

can hardly have been more than slight, date back to surprisingly early times. For example, in Greek times quite good estimates of the size of the earth and the distance of the moon were made, and even the slow conical movement of the earth's axis which takes 26,000 years for its completion had been detected.

In the western world, astronomy, like the other sciences, suffered an almost complete eclipse between the end of the Greek civilization and the Renaissance. For the next great blossoming of astronomy we must turn to the fifteenth, sixteenth, and seventeenth centuries when astronomy gained a new importance in connection with navigational problems. The voyages of discovery had enlarged the known world, wealth was to be had in overseas trading ventures, but to gain it the hazards of the sea had to be dared. As each maritime power extended its overseas trade it began to feel the need for a safe method of navigation on the high seas. The rulers of Spain, Portugal and France offered prizes for advances in navigation: Britain established a Commission for the Discovery of the Longitude in the seventeenth century.

To understand the problem we must go into the matter in a little more detail. To discover position at sea requires a comparison of the aspect of the stars as seen by the mariner with their positions as seen *at the same moment* from some fixed station. This implies the existence of a fixed station, at which observations and calculations may be made, and this Britain had in her Royal Observatory at Greenwich founded by Charles II. It also implies the existence of a clock which even when aboard ship, will keep time with a clock at the fixed station. Without a clock the mariner may determine his latitude but he cannot find his longitude. The clocks of the seventeenth century were all controlled by the swing of a pendulum which would not beat true aboard a rolling ship, and all efforts to insulate a pendulum from the effects of the ship's motion having failed, other methods were eagerly sought.

In particular it was realized that the rapid, but uneven, motion of the moon against the background of the stars might provide a substitute clock by whose aid the mariner would in effect be able to tell the time if only the future position of

the moon could be accurately predicted. Methods were developed by which the mariner might determine his position to within sixty miles once the lunar problem had been solved. Unfortunately the problem of the motion of the moon is probably the most complex problem in any science, but, although some of its difficulties must have been realized at the time, in default of anything better it had to be tried. The matter was one of great public urgency: in 1713 representations were made to Parliament as the result of serious losses of shipping. A commission was set up, before which Sir Isaac Newton appeared as the principal witness, and he, although realizing some of the tremendous difficulties of the lunar method, favoured it for want of a sea-going time piece. The prize of £20,000 offered for a method of navigation accurate to within 30 miles was eventually won by Harrison for his invention of the chronometer, which completely superseded the lunar method for navigational purposes, but the concentration of attention on the motion of the moon and the attempts to solve it had far-reaching effects.

It led to important advances in methods of calculating the motions of planets, satellites, and comets, and, at a later date, of stars. It influenced methods of calculation and led to the development of new concepts of pure mathematics: it exercised a general stimulating effect lasting for two centuries on branches of science quite unrelated to astronomy, and on the work of scientists who probably themselves did not realize its influence.

By the middle of the nineteenth century it had become possible to predict the position of almost all planets and satellites to a very high degree of accuracy, and this almost god-like power of prediction took hold of the imagination of astronomers and laymen alike. It may well have been the success of this type of investigation which encouraged in Britain especially the thoroughly mechanistic philosophy so much in tune with the outlook of a nation growing rich by its mechanization of industry. Certainly there has rarely been a time when popular astronomy was more truly popular and when it exercised so marked an influence on contemporary thought.

Towards the end of the nineteenth century a change took

place. Astronomers such as Huggins and Lockyer began to found the science of astrophysics which has a larger horizon than the solar system. The stars became the chief object of study, which in itself was not new, but whereas before the stars had been used simply as markers of positions on the sky, and the main question had been to determine their positions very exactly, now the problems were to find out about the actual constitution of the stars—what they were made of, how hot they were and so on.

This cannot be done directly because the stars are utterly inaccessible. It must be done through a knowledge of the behaviour of hot gases and by the application of physical laws discovered in terrestrial laboratories. It involves in particular a knowledge of the behaviour of atoms, and it is probably not too much to say that many of the trains of thought and investigation which led to the modern atomic theory owe their origin to astronomical discoveries. As the theories developed further, mainly as the result of laboratory investigation, they were applied to stellar studies. In the space of a few years the centre of interest shifted away from problems of the movement of planets and of stars (dynamical astronomy) to astrophysics, which rapidly became more and more indebted to general physics as its progress was maintained.

In sketching rapidly over the history of any science there is a temptation to fall into one of two errors. Either we see only the practical problems such as those of the calendar and of navigation and neglect the fact that once these practical problems had been solved the intellectual enthusiasm of the scientists carried them on to further advances; or we see nothing apart from this enthusiasm and interpret the story of scientific progress exclusively in terms of the curiosity of thinkers isolated from the world. The latter view is enshrined in the popular conception of the absent-minded professor and it is therefore necessary to lay stress on the severely practical needs which formed the genesis of many investigations even in so unworldly a science as astronomy. But once having drawn attention to the problems of the calendar and of navigation which set in train the investigations of the ancient world and of the seventeenth century, let us not go to the other extreme by disregarding subsequent progress, which, at

the time when it was made had little or no significance outside astronomy itself.

We can perhaps not unfairly represent the history of astronomy as a series of epochs in which the driving force of progress was alternately the severely practical needs of civilization in development and the devouring but disciplined curiosity of your true scientist.

In the modern period of the application of physical laws to the study of the stars, we are, perhaps, seeing an epoch of the second kind, when astronomy, although the source of the first impetus to the study of atomic behaviour, progresses by the application of atomic knowledge gained outside its own special domain. But, if we may hazard a guess of the future, it seems probable that the time is coming when astrophysics will reach a stage of development sufficiently advanced to permit a repayment of its debt to physics: when the stars may be regarded as experiments, uncontrollable but comprehensible, whose results will be of value to other sciences and for practical applications.

It is astronomy in the approach to this state which is described in this book, where the reader may find the answer to his question 'what good is astronomy?' In the past astronomy has explained our material surroundings to us, and has given us some control over them. It has played a part in freeing mankind from mental and physical bonds, and we ought not to doubt that it still has services of the same kind to render. We can perhaps guess at what lies over the frontier by surveying the territory which lies on our own side of it.

Chapter Two

THE ASTRONOMER'S WEAPONS

Telescopes.

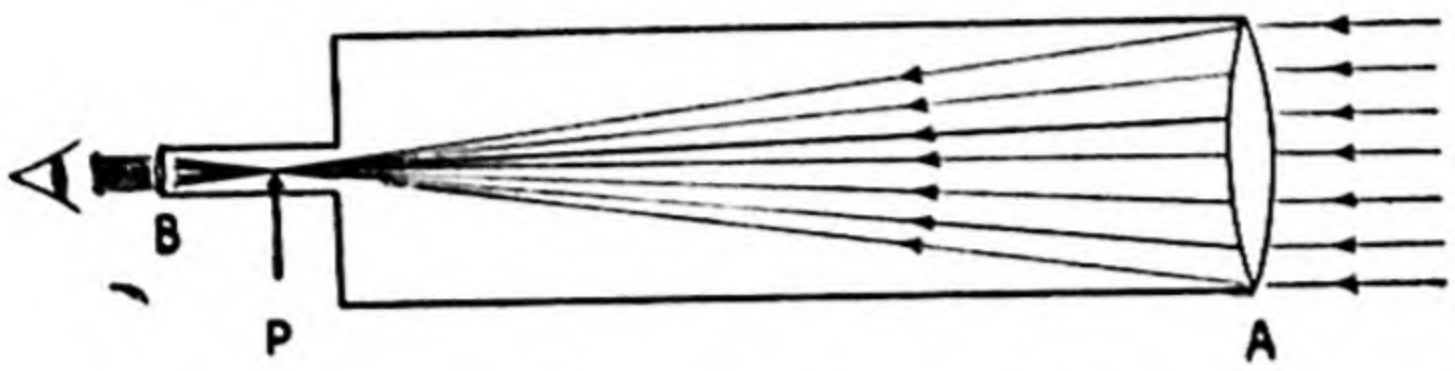
A FAMOUS astronomer once said that all our information about the stars had come to us on a ray of light. The astronomer's instruments are therefore all concerned with light: with its collection, and with its analysis in various ways.

The man in the street thinks first of the telescope, and this is the natural place to begin, but it must be emphasized that for many purposes the function of the modern astronomical telescope is not to produce the largest possible image, but to collect as much light as possible.

Telescopes fall naturally into two classes, the refractors and the reflectors, of which the first is the older form. A crude refracting telescope can be constructed out of almost any two lenses of which the front or objective lens should be the larger, and should also have the greater focal length (see Fig. 2) while the second, or eye, lens should be smaller and have a shorter focal length. This follows because the only light which enters the instrument is that which falls on the objective lens and so this should be as big as possible: the magnification produced by the telescope is the ratio of the focal length of the objective to that of the eye lens, so that for high magnification the focal length of the objective must be as large as possible while that of the eye lens must be as small as possible.

When telescopes of this simple pattern were first constructed in the seventeenth century it was discovered that they suffered from certain defects of which the most important was *chromatic aberration.* When red light passes through a simple lens it comes to a focus further behind the lens than the focus for blue light. Thus if we observe simultaneously a group of stars, some of which are red and some blue, then our eye lens will have to be pulled out a little to give a sharp image of the red stars, and pushed in a little to give a sharp image of the blue stars. In fact, we shall never be able to get either

Fig. 2. THE REFRACTING TELESCOPE



Parallel rays of light reaching the 'object lens,' A, are brought to a focus at P. The distance AP is the 'focal length' of A. The rays pass through a second 'eye lens,' B, of short focal length (PB) and, becoming parallel, pass into the eye which sees an image of the star.

The magnification is AP/BP, so that for high magnification A must have a much larger focal length than B. The light collecting power of the telescope is proportional to the area A, so that to produce bright images of faint stars the diameter, or 'aperture,' of A must be large.

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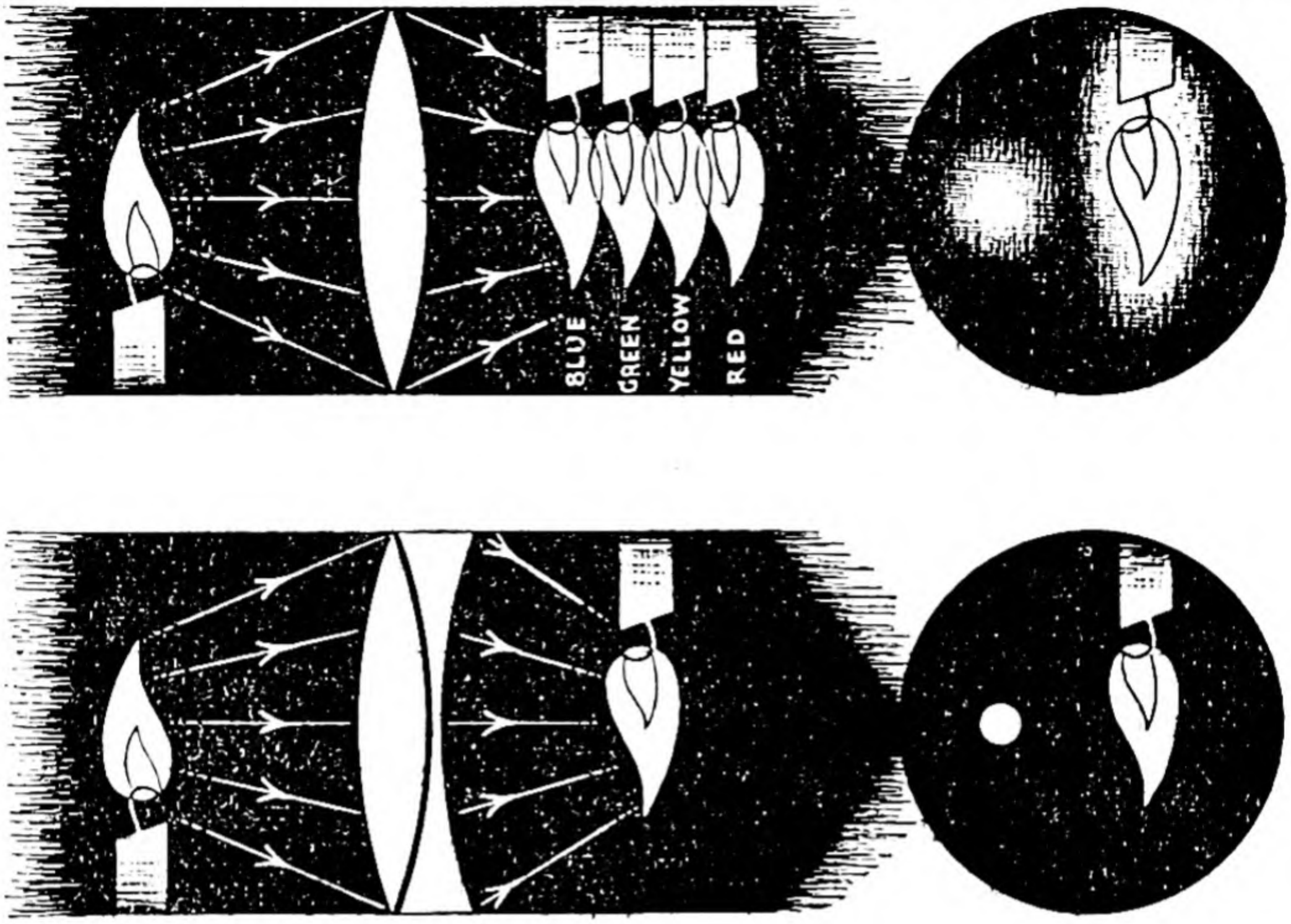
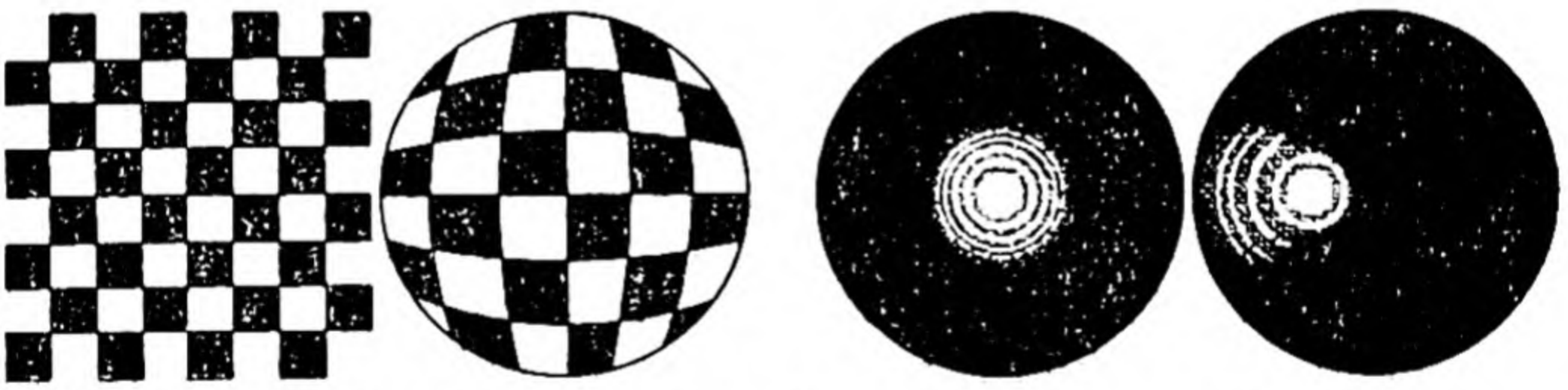
a visual impression or a photograph in which all the stars are sharply focused at the same time. The situation is actually worse than this since no stars are either pure red or pure blue in colour, and what happens is that, if we observe a single star, we shall see either the red light from it in sharp focus surrounded by a blue halo, or, if the eye lens is pushed in until the blue light is in focus, the image will be spoiled by a red halo.

It is possible to effect a partial cure of this defect by replacing the simple objective lens by two lenses made of different sorts of glass whose shapes are accurately calculated. The splitting of white light into the red, blue and other colours which is produced by the front lens of the pair is then corrected by the second lens, and both red and blue rays are then brought to a focus at the same point. This does not correct the error completely. Red and blue are the extremes of visible light and between them come orange, yellow and green. Using an objective with two components only halves the error, by, as it were, taking the line of different coloured images and folding it in half, so as to bring the red and blue together. This will also bring the orange and yellow images together, but at a slightly different point, while the green image will be formed at yet a third point. However, this residual error is often so small as to cause no serious inconvenience.

Isaac Newton was aware of this defect of the refracting

Fig. 3. WHAT HAPPENS TO LIGHT WHEN IT GOES THROUGH A TELESCOPE





A simple lens produces separate coloured images. Through such a lens a candle might be seen as a sharp red image surrounded by a blue blur.

A star has a fuzzy appearance.

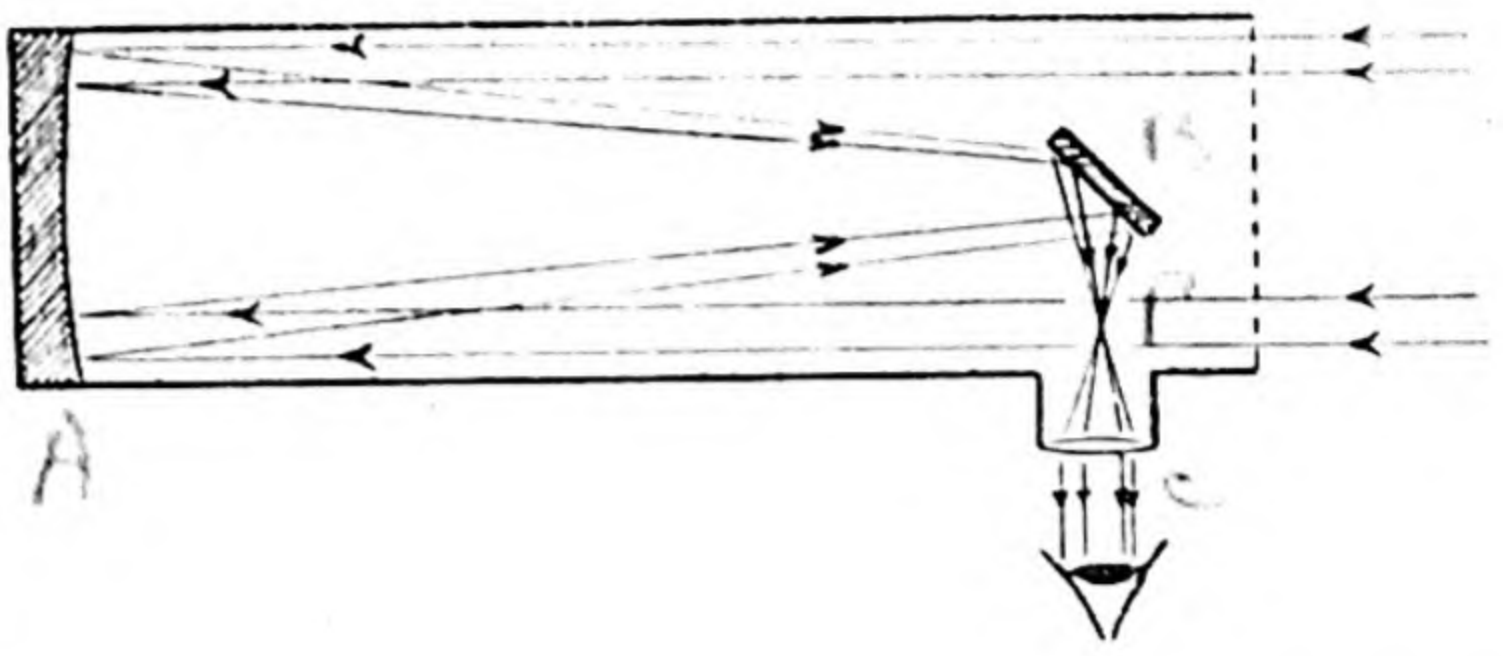
Two matched lenses of different kinds of glass give coincident images. Through this compound lens the candle and star may be seen sharply in their true colours.

A chess board seen through a badly designed telescope is distorted. This effect is called spherical aberration.

Even though a star is only a point of light, the telescope produces an image consisting of a central blob of light surrounded by several faint rings. At the centre of the field the rings are symmetrical. At the edge they are thrown to one side forming a small ' tail ' of light. This defect is called coma.

Magnification is not everything. A big telescope shows more detail than a small one with the same magnification.

Fig. 4. THE REFLECTING TELESCOPE OF NEWTON



Parallel rays are reflected from the surface of the concave mirror, A. The small plane mirror, B, turns the reflected rays out to the side of the telescope tube, where they come to a focus at P. They are then rendered parallel by a lens C, and enter the eye.

telescope and believed that there was no method of curing it. He turned his attention to the reflecting telescope where the rays are brought to a focus by reflection from the surface of a curved mirror, light of all colours being reflected in exactly the same way. In modern practice the mirror is made of glass or fused quartz, its surface is shaped with extreme accuracy, polished, and covered with a very thin layer of silver or aluminium at which the light is reflected *without ever passing into the glass*. In Newton's day and up to the nineteenth century, an alloy known as speculum metal was used. This gave a good reflecting surface when freshly polished, although it tarnished rapidly, and the mirrors were fashioned from solid discs of this material.

The first successful reflecting telescope was constructed by Newton himself in 1672 with his own hands, and its optical system is illustrated in the figure (Fig. 4). The design of such telescopes had been under discussion for forty years and some previous rudimentary instruments had been attempted. Newton's instrument has a useful aperture of 1½ inches and a focal length of 6⅓ inches. The use of a small inclined mirror (in modern instruments a right-angled prism is sometimes used) to throw the image out at the side, is due to Newton and this system is still known as the Newtonian reflector.

In the construction of a small telescope the chief difficulties are optical—the problems of shaping the components correctly, the application of metal films of high reflectivity to the mirror surfaces, and so on. The mechanical difficulties are not great, and any skilled garage hand can easily construct all the mechanical parts for a small telescope. In fact, old motor-car spares

and garage workshops play quite a large part in the amateur construction of small telescopes.

As soon as we turn to large instruments the mechanical difficulties become much more formidable. The mirror of a six-inch reflector may weigh a few pounds. The mirror of the new two-hundred-inch telescope on Mount Palomar in California weighs 14½ tons. The six-inch mirror may be mounted in a very simple cell, while the 200-inch mirror is held on a complicated system of 36 supports mounted on balanced levers. The object is to afford uniform support of the mirror all over its back surface, into whatever posture it may come as the telescope is turned to follow the apparent movement of a star resulting from the rotation of the earth on its axis. The importance of a uniform support of this kind is that a disc of glass of such great size is liable to the danger of distortion under its own weight, and, since the whole effort of the mirror constructors and designers has been aimed at producing a surface correctly shaped to within less than one hundred thousandth of an inch, failure to prevent distortion of the surface would vitiate all the work of the opticians.

This consideration of distortion of the main objective is one of the main reasons why all modern large telescopes are reflectors. The largest refractor has a diameter of only forty inches and is part of the equipment of the Yerkes Observatory in the United States. There seems to be very little possibility of this size being greatly exceeded in the future, whereas the Palomar reflecting telescope has a diameter five times as great. Contrasting the two types of instrument it will be noted that the lens of a refracting telescope can only be supported at its edges if the aperture is to be left free for the passage of light rays. For a small lens this is of no great importance, but for a lens weighing many hundredweight, the support which could be given in this way would be quite inadequate, and the lens would sag slightly and lose the form which had been imparted to its surfaces with so much care and effort. Again, the light rays pass through a lens, and will suffer distortion at every bubble or fault which they may meet in passing through the glass. It is unfortunately very difficult to cast a disc of glass of any size which is completely free from

faults, and the problem becomes rapidly more severe as the size increases.

These difficulties must be contrasted with those offered by the reflector where the function of the glass is simply to provide one single curved surface carrying a thin film of aluminium, where the light does not penetrate into the glass, and where distortion can be reduced by supporting the disc at all points of its back face. For small telescopes these advantages are to some extent offset by the fact that the surfaces of a lens need to be shaped to an accuracy only about half that of a mirror producing a similar image, but this advantage is considerably reduced by the fact that a reflector has only one mirror surface, whereas in a refractor the two components of the objective have four surfaces which must be optically worked. However, among small instruments refractors are possibly more common than reflectors and even for moderately large instruments especially for photographic observations, the superior quality of the images produced by refractors makes them preferable to the less expensive reflectors. It is in the class of very big telescopes that the reflector holds unchallenged superiority.

Large reflectors are usually constructed so that they may be used in a variety of ways. In the case of the two-hundred-inch telescope it is possible to use the instrument in a way which dispenses with the Newtonian mirror for turning the light beam out to the side of the telescope tube. An observing chair is mounted on gimbals within the telescope tube itself. Here the observer will sit with nothing but the sky above him and the huge sheet of glass below, from which the rays will come to an eyepiece or camera between his knees. However the incoming beam must be interrupted as little as possible so that only small pieces of apparatus may be mounted in the tube, and a Newtonian mirror is provided which can be swung into position so as to throw the beam to the side, where it may be received by a camera or spectroscope. A limit to the size of apparatus which may be mounted even in this position is set by the fact that too great a load would produce a slight but important deflection of the tube structure which would vary according to the posture into which the instrument was turned.

Heavy equipment must be mounted as near to the point of support as possible and so a second mirror with a convex surface is provided which, when swung into position will return the beam down the axis of the instrument where it will pass through a hole in the centre of the main mirror and into the recording or analysing apparatus. This third alternative is a form of telescope first suggested by the seventeenth-century French astronomer, Cassegrain, and called after him, its advantage being that it brings all the heavy components of the instrument as near as possible to the point of support.

Further steps still have been taken in the direction of turning the modern large telescope into a collector of light. Most large modern reflectors incorporate a system of secondary mirrors arranged to pass the beam through the hollow axles of the mounting and down to a cellar where heavy apparatus for the analysis of light may be set up, this being possible because the final beam from the telescope is in a fixed direction, no matter how the instrument may be turned.

The subject of the performance of telescopes is worthy of some further consideration. When we consider a single star, one of the main considerations is the amount of its light which can be collected. The unaided eye collects only the light which falls on the pupil, which is a circle with a diameter of about one eight of an inch, or an area of about one hundredth of a square inch. In contrast, the two-hundred-inch telescope collects all the light on a circle of 200-inches diameter, having an area of about 30,000 square inches. That is to say, the Palomar telescope collects about thirty million times as much light from each star as the unaided eye does, and so should enable a star to be seen thirty million times as faint as the faintest visible to the naked eye.

When we consider groups of stars, especially those which appear very close together, or objects such as planets or nebulæ which present extended images, then another factor known as resolving power becomes of importance. If two lines are drawn on a piece of card at a distance of one inch apart, then the normal eye can just distinguish them as two separate lines when the card is a hundred yards away. This is the limit of resolution (about one minute of arc) of the naked eye, and is imposed, partly by the size of the pupil, and partly

by the fact that the sensitive retina of the eye is composed of a very large number of nerve-endings. If the images of two objects fall so close together on the retina that they are both on the same nerve-ending then the two objects will not be seen separately.

A familiar example of the way in which this sets a limit to the visibility of detail is provided by the dot structure or 'screen' of newspaper photographs. With a magnifying glass it can be seen that each picture is built up of an enormous number of black dots on a white ground, the general degree of shading of any part of the picture being produced by varying the size of these dots. In the high-lights they are very small, while in the shadows they are so big that they run into one another. But a dot is a dot, big or little, and has no character beyond that. Once you have magnified your picture so as to bring out the dot structure, further magnification does no good and shows no additional detail. The screen of the picture sets a limit to the smallness of the detail which can be extracted from it no matter how much it is magnified: no detail so small that it would fall on only one dot can ever be included in the picture.

The resolution of a telescope is of a rather different kind. No telescope at present in use will ever show a star as more than a point of light, but the image of a point of light which a telescope produces is not a point, but a small circular blob of light surrounded by a number of faint rings. These are produced entirely by the telescope and cannot be eliminated, and the smaller the telescope the bigger the blob of light appears to the observer. If two stars appear very close together, a small telescope will not show them separately because the two light blobs will fall on top of one another, and this will be true however much magnification is employed.

An extended image, like the illuminated disc of a planet can be thought of as a whole series of points of light all running into one another with no gaps, and each of these is shown by the telescope as a small blob. Now suppose there is a small black spot on the planet. In the telescope it will be visible only if the blobs of light from the neighbouring bright parts of the planet do not overlap and swamp it. If they do, increased magnification will do no good because blobs and

spot will be magnified together. The only thing to do is to take a larger instrument which produces relatively smaller blobs which will not overlap on to the spot, and it will therefore be visible.

The upshot of this discussion is that, just as in the case of the newspaper photograph there is a useful limit to magnification, or, to put the matter the other way round, there is a limit to the smallness of detail which can be made visible in a telescope of given size, and magnification beyond that necessary to show this is of no value. The larger the telescope, the smaller the detail which can be seen, and the higher the magnification which may usefully be employed so that large telescopes have a special value for the revelation of, for example, planetary details (Fig. 3).

Just as the resolution of detail in the images of planets and nebulæ had to be discussed in terms slightly different from those appropriate to the discussion of single points such as stars, so must the question of the brightness of stars and nebulæ seen in a telescope. We have seen that the apparent brightness of a star is increased by using a telescope, for the telescope takes all the light which it collects, and packs it into the same point of the image. This is not so with an extended object: the telescope collects more light but it also stretches out the image, so that the increased light is spread over an increased apparent surface. In fact, it can be shown that a telescope can never increase the brightness per unit area of an image, and, if the instrument is badly designed it may fall very far short of the ideal. If a nebula or gas cloud looks faint to the naked eye, it will continue to do so in a telescope. Here the photographic plate has a part to play, for the telescope can be used as a camera and may be kept pointed at the object under observation for many hours, while the photographic plate sums up all the light falling on it. The eye is at a disadvantage since it must always take an instantaneous impression.

However, if the telescope is badly designed the photographic exposures may be prohibitively lengthy, and so, for photography of nebulæ and similar faint extended objects, the best design must be achieved. The shorter a telescope is in comparison with its diameter, the better it is for this purpose, and it

will be noticed that all modern telescopes have a short, stubby appearance.

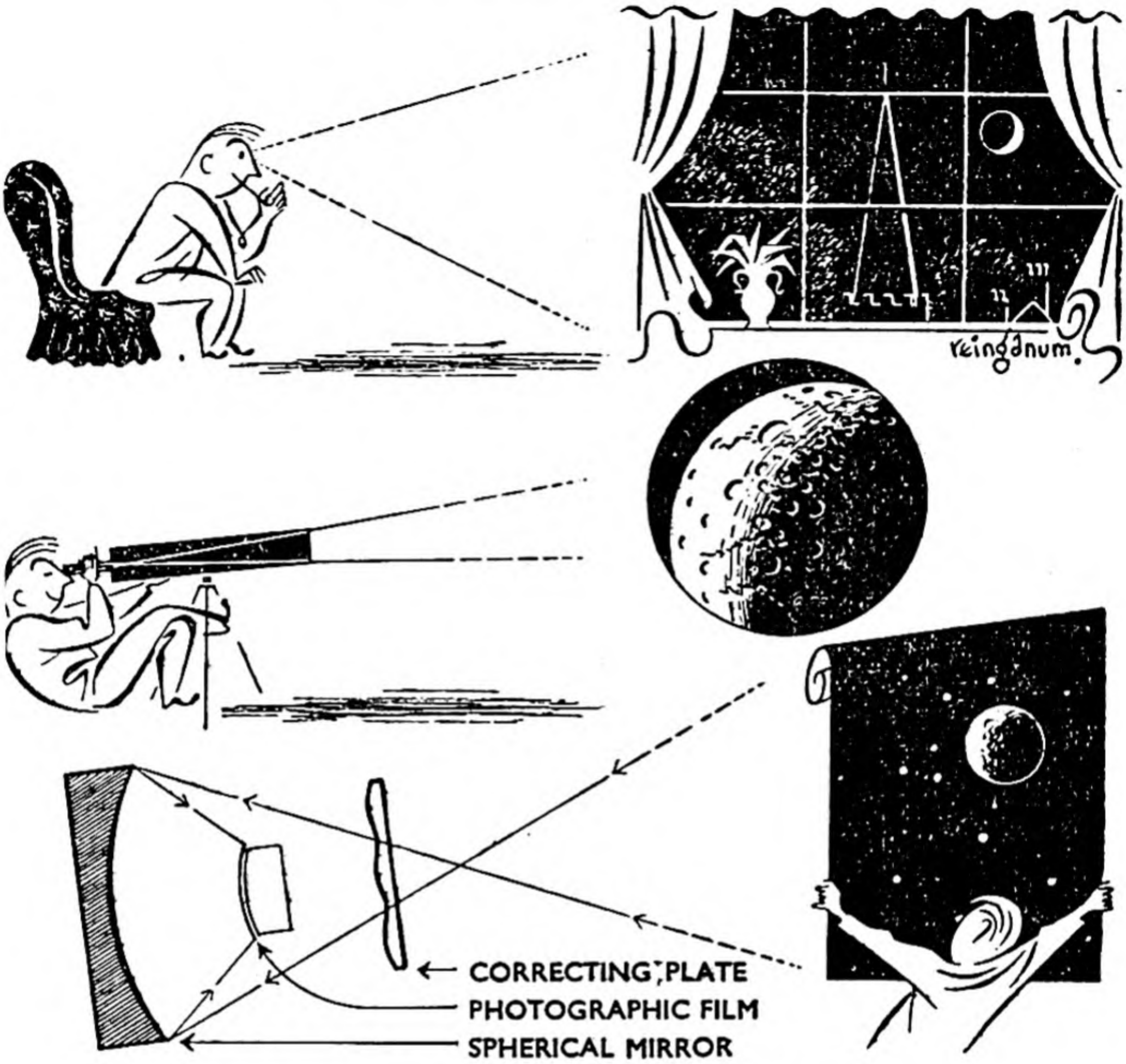
Unfortunately this introduces complications, and exaggerates certain errors of image formation. Essentially a telescope consists of two or more optical components (lenses or mirrors) arranged in line. This line is the axis of the instrument, and the image of a bright source is best when it is formed near this line, i.e. near the centre of the field of view of some one looking through the instrument. When the source is seen obliquely and the image is formed at the edge of the field of view, two new defects become apparent. One of these is coma, which means that a star seen near the edge of the field looks as though it had a short bright tail running out from it (Fig. 3). This error can be seen in very gross form in a home-made telescope constructed out of two lenses and a cardboard tube. It is almost impossible to get the lenses properly square and lined up, and in consequence such an instrument is almost certain to show coma.

The other defect, spherical aberration, can be illustrated by imagining a telescope pointed at a pattern of squares such as a chess board. Those near the centre of the field are the right shape, but the outside ones appear curved and distorted.

Both these defects become most pronounced at the edge of the field, i.e. when the rays make a considerable angle with the telescope axis. In most ordinary telescopes this angle is quite small. The moon will usually fill the field, which means that the front lens only lets in rays at an angle of about $\frac{1}{4}°$ to the axis. This is minute by comparison with the field of vision given by the eye, which can at least glimpse objects about 60° off the axis. To make a short stubby telescope suitable for photography of faint nebulæ we must collect rays which come in at an angle of several degrees with the axis of the telescope, and this raises the difficulties not only of the optical errors, coma, and spherical aberration, but also of the manufacture of the lenses or mirrors which have to be relatively much more deeply curved.

The ideal telescope would have no axis at all, and would bring all rays to a perfect focus. A close approximation to this ideal has been achieved with the Schmidt camera. Its essential component is a spherical mirror, which, owing to its

Fig. 5. THE SCHMIDT CAMERA



The unaided eye has a wide field of vision.

The ordinary telescope gives magnification but restricts the field.

The Schmidt camera gives a wide field with such high resolution that photographs taken with it may be magnified many times.

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symmetry has no axis. Unfortunately a spherical mirror does not form perfectly sharp images. The Schmidt camera therefore incorporates a thin glass correcting plate of varying thickness which is placed in front of the mirror and just deviates the outer rays enough to bring them to a true focus, but without introducing errors at the edge of the field. The arrangement is illustrated in the diagram (Fig. 5). The large spherical mirror of very short focal length receives the light through the correcting plate and forms an image on a film pressed on to a specially curved former. This arrangement is remarkably powerful and

flexible, and cameras have been constructed with focal lengths actually less than their diameter, allowing the production of very bright images of extended objects. In addition the instrument has a wide useful angular aperture, and photographs have been made which included the whole of a constellation such as Orion which is over 20° across. The Schmidt camera can do very important work in discovering faint objects and in particular in tracing out the very faint edges of nebulæ. By its aid it has been discovered that many nebulæ extend far beyond the limits which were indicated by photographs taken with older equipment.

For reference we include a short table of the world's larger telescopes:

Reflectors			*Refractors*		
Observatory	*Diameter (inches)*	*Date*	*Observatory*	*Diameter*	*Date*
Mt. Palomar, Cal.	200	under construction.	Yerkes, Wis.	40	1897
Mt. Wilson, Cal.	100	1917	Lick, Mt. Hamilton, Cal.	36	1888
McDonald Obs., Texas.	82	1939	Meudon (Paris Observatory).	33	1896
Radcliffe Obs., Pretoria, S. Africa.	74	under construction.	Potsdam, Germany.	32	1905
Toronto, Canada.	74	1933	Allegheny, Univ. of Pittsburgh Obs., Pa.	30	1912
Victoria, B.C. Canada	72	1919	Pulkovo, Leningrad	30	1886
Perkins Obs., Ohio.	69	1932	Nice (Paris Observatory)	30	1887
Harvard Coll., Obs., Mass.	61	1934	Royal Observatory, Greenwich.	28	1894
Mt. Wilson, Cal.	60	1908			
Harvard Station Bloemfontein, S. Africa.	60	1933			

36-inch reflectors at Solar Physics Observatory, Cambridge, England, Royal Observatory, Edinburgh, and Royal Observatory, Greenwich.

It is worth noting that all the reflectors over 60 inches diameter have been constructed since 1900, whereas the maximum size for refractors was reached in 1897 and only two large refractors have been constructed since 1900.

The three largest reflectors in Britain are all of only 36-inch aperture.

It must be admitted that a telescope of 100 inches in diameter could not be used with profit anywhere in Britain for making the kind of observations which are undertaken with large telescopes in the U.S.A. and S. Africa. Such a telescope needs a climate giving clear, pitch-black nights since it is capable of picking up stars very little brighter than the blackest sky-background encountered anywhere on earth. It must be at an altitude so great that as much as possible of the earth's atmosphere and its attendant disturbances are left below: the site must be remote from the lights of towns and in a region where the air is as free as possible from dust. It must, at the same time, be accessible to electrical and water supplies and other essential laboratory facilities. Geographically it should be in a moderate north or south latitude where most of the stars can be seen at one season or another of the year, and preferably in the southern hemisphere, since, for reasons of history, most observatories have been established in the northern hemisphere, leaving the southern stars relatively less well studied.

Remarkably few sites fit these conditions: they include the mountains of North America, and particularly California: the mountains of South America and the South African veldt, and parts of Australia. In all these regions observatories have been established: in addition the uplands of Central Asia may provide good sites when obvious difficulties of transport and supply have been overcome.

But we ought not to conclude from this that observational astronomy in Britain must be a second-rate affair following the lead of the U.S.A. and South Africa, but lagging behind because of inferior equipment and an unsuitable climate. Long-distance observation of faint objects may be impossible, but we are not so familiar with the brighter visible stars that we can afford to neglect them as a field of research. The effect of such a restriction may indeed be salutary: there would be less temptation to make general surveys of the sky and more inducement to attempt a really thorough study of a comparatively small number of stars. If there is to be anv

hope of drawing valuable lessons of atomic physics from stellar studies, these must be intensive and detailed, rather than extensive and superficial.

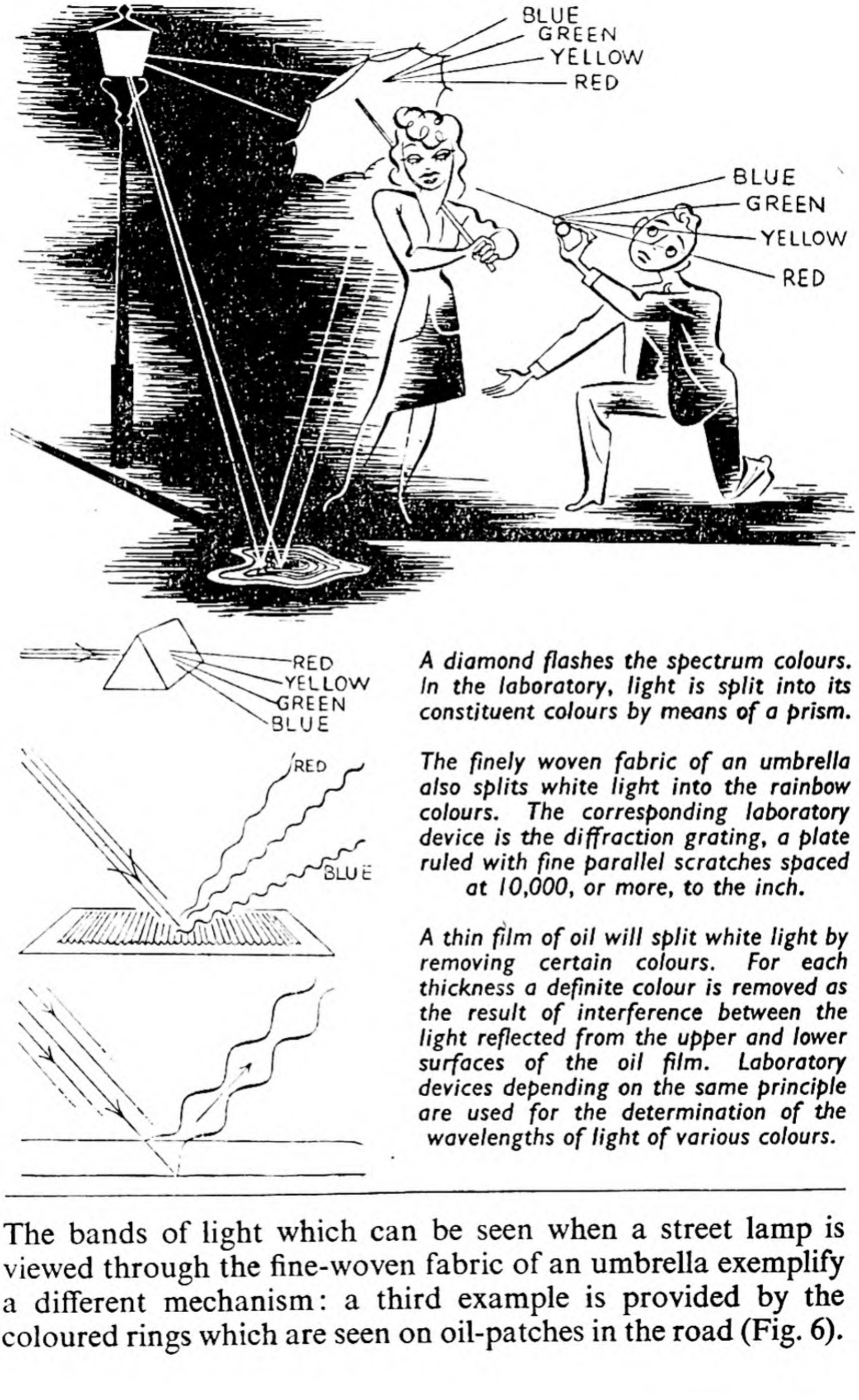
The obstacle is lack of suitable equipment and of financial support. The equipment might well be of a kind completely different from orthodox telescopes and, in the view of some astronomers, might be an adaptation to stellar observations of the type of solar telescope described in Chapter VI. There is no reason whatever to encourage an inferiority complex about British astronomy, and every reason to believe that results of very great theoretical and practical importance might come from programmes of investigation specially adapted to conditions here.

The Analysis of Light.

Reference has already been made to the analysis of the light from stars. It is a fact of common observation that the stars are coloured—the sun, and Capella, prominent in Britain's winter sky, are distinctly yellow: Betelgeuse, the top left-hand star of Orion is a deep red: Vega, in the zenith of a summer midnight, is a steely blue, and so is Sirius, brightest of all the visible stars, which may be located by extending Orion's belt downwards. As we shall see, these differences of colour are a direct indication of differences in the temperatures of these stars. The yellow stars have surface temperatures of about 5,700° C, the red stars about 3,200° C, while the blue stars are much hotter with temperatures of 10,000° C or more. The quality of redness or blueness is a rather crude way of expressing the fact that a star emits more red light, or more blue light than light of any other colour, and a closer analysis, resulting in a determination of exactly how much light of any colour is emitted by each star yields more detailed information about stellar structure.

There are a variety of instruments for analysing the light from any star into its constituent colours, but this same separation can occur naturally. A diamond ring flashing red, orange, green and blue as it is turned in the lamp-light, splits up the light as the result of one kind of physical phenomenon.

Fig. 6. THE ANALYSIS OF LIGHT



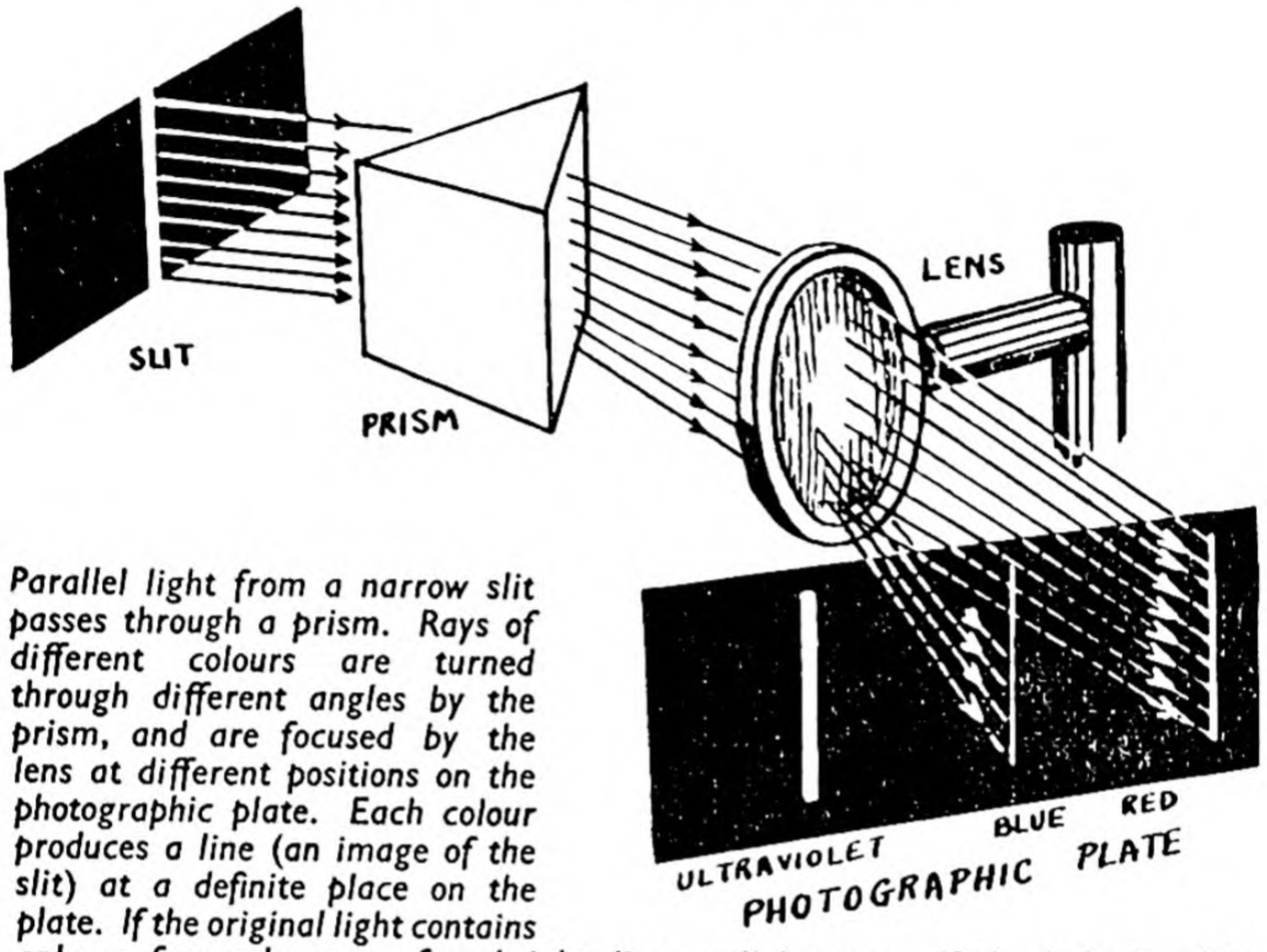
A diamond flashes the spectrum colours. In the laboratory, light is split into its constituent colours by means of a prism.

The finely woven fabric of an umbrella also splits white light into the rainbow colours. The corresponding laboratory device is the diffraction grating, a plate ruled with fine parallel scratches spaced at 10,000, or more, to the inch.

A thin film of oil will split white light by removing certain colours. For each thickness a definite colour is removed as the result of interference between the light reflected from the upper and lower surfaces of the oil film. Laboratory devices depending on the same principle are used for the determination of the wavelengths of light of various colours.

The bands of light which can be seen when a street lamp is viewed through the fine-woven fabric of an umbrella exemplify a different mechanism: a third example is provided by the coloured rings which are seen on oil-patches in the road (Fig. 6).

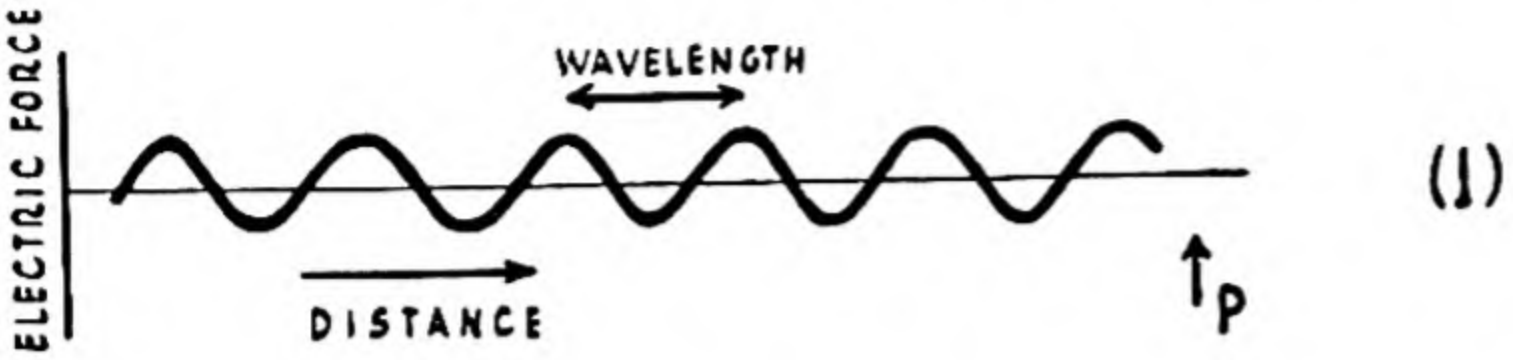
Fig. 7. THE PRISM SPECTROSCOPE



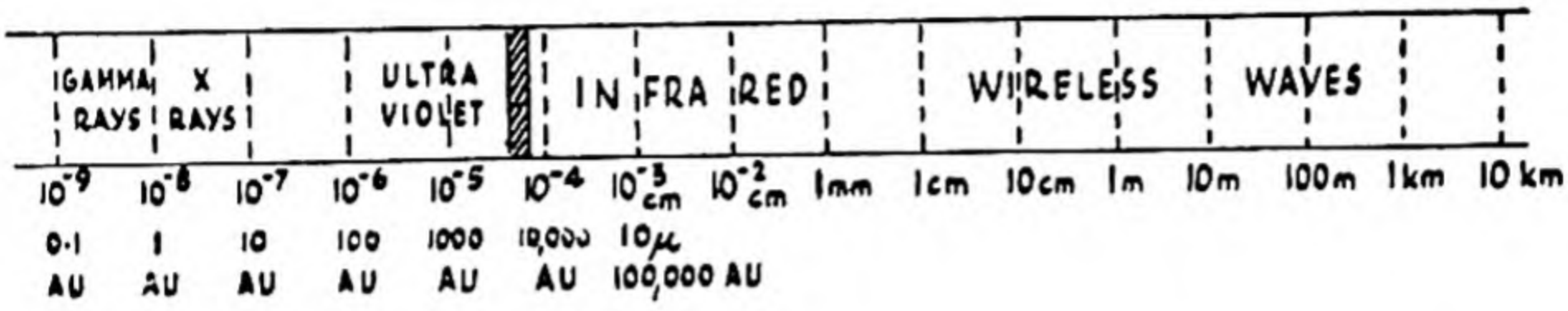
Parallel light from a narrow slit passes through a prism. Rays of different colours are turned through different angles by the prism, and are focused by the lens at different positions on the photographic plate. Each colour produces a line (an image of the slit) at a definite place on the plate. If the original light contains only a few colours, a few bright lines will be seen. If the light is white (containing all colours) a continuous strip will be produced. If a colour is absent from the original white light there will be a dark gap or line in the spectrum at the place where the missing colour would have appeared.

The method of analysis analogous to that of the diamond is by means of the prism spectroscope (Fig. 7). Light coming from a star is passed through a narrow slit, and this line of light then passes through a prism of glass, quartz, or in special types of work, other transparent materials. Light of each colour pursues a slightly different path through the prism, the blue being deviated more than the red, and when the rays issuing from the prism are brought to a focus, for example on a photographic plate, a strip of light is produced in which the colours are arranged in the rainbow order—red, orange, yellow, green, blue, indigo and violet. In addition to these visible colours there are other radiations, invisible to the human eye, which can be detected by the photographic plate or by other means. The only difference between visible light and these invisible radiations is one of wavelength. Light, both invisible and visible, consists of a series of waves or electric and magnetic

Fig. 8. SOMETHING ABOUT LIGHT WAVES

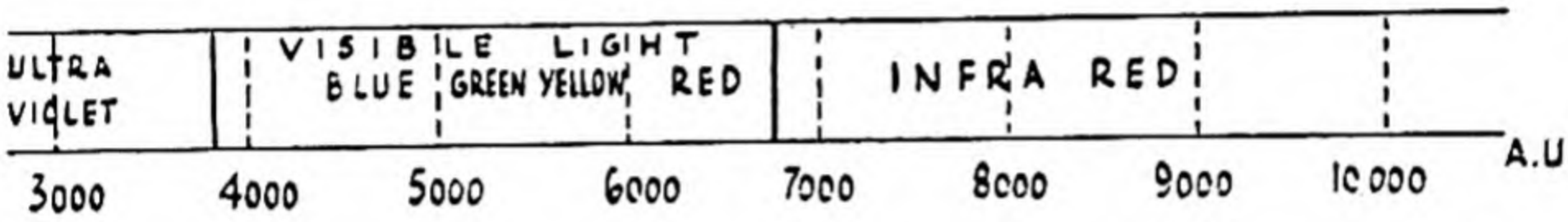


(1)


GAMMA RAYS
X RAYS
ULTRA VIOLET
INFRA RED
WIRELESS WAVES
10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ cm 10⁻² cm 1mm 1cm 10cm 1m 10m 100m 1km 10 km
0·1 AU 1 AU 10 AU 100 AU 1000 AU 10,000 AU 10μ 100,000 AU

(2)

(3)



Light waves are only a particular kind of the general species known as electro-magnetic radiation. All these radiations are a system of waves consisting of a variation of electric force with distance as shown in (1). *The distance between two peaks is called the wavelength. These waves move through space at a speed of 186,000 miles (300,000 kilometres) per second. If we consider a point P the number of waves which pass in one second is called the frequency, and is equal to the number of wavelengths in a distance of 300,000 kilometres. The shorter the wavelength the higher the frequency.*

Wireless waves, infra red or heat rays, visible light, ultra-violet rays, X-rays and the gamma rays of radium are all examples of electromagnetic radiation, and differ only in wavelength. For wireless waves a suitable unit for measuring wavelength is the metre or kilometre. For infra-red rays a suitable unit is the μ *(mu) equal to one ten-thousandth of a centimetre. In astronomy and spectroscopy a suitable unit is the Ångstrom Unit, one hundred millionth of a centimetre.*

Scale (2) *shows the wavelengths of various kinds of radiation. The shaded area represents the whole range of wavelengths to which the eye is sensitive.*

(3) *shows this range on a larger scale and the wavelengths in Ångstrom units of light of various colours is indicated.*

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vibrations which advance at the constant speed of 300,000 kilometres or 186,000 miles per second. We tend to give different names to electro-magnetic waves of different wavelength because we must use different means to detect them, but they are all of the same nature. Those with wavelengths from about 2,000 metres down to a few metres or less are called radio waves and are detectable by wireless sets of various

kinds. Those from a millimetre down to one thousandth of a millimetre are heat waves, detectable by the heating of a blackened surface which absorbs them, or, for the shorter wavelengths, by photography. They are also known by the general name of 'infra-red' because they are of a wavelength greater than that of visible red light (Fig. 8).

For visible light, centimetres and millimetres are too large to serve as a convenient unit of measurement, and the unit generally adopted is the Ångstrom unit which is a length of one hundred millionth of a centimetre (10^{-8} cm.). In these units the reddest light visible has a wavelength of about 7,000 Ångstroms, yellow light about 5,900 Ångstroms, blue light 4,500 and the deepest violet colour visible to the eye has a wavelength of just under 4,000 Ångstroms. Shorter wavelengths are called 'ultra-violet,' while in the region from a few hundred Ångstroms down to about one Ångstrom or less, we come to the X-rays. Radiations of still shorter wavelengths than this occur when atoms break down naturally as the result of radio-activity or are broken up in atom-smashing experiments. There is thus an immense range of wavelengths, and our eyes are only sensitive to a tiny section of it. In ordinary spectroscopy or light analysis of the stars we deal mainly with the visible region including the near infra-red and ultra-violet, and the spectroscope sorts out the light of each wavelength (i.e. colour) and arranges them in order, producing a luminous band known as a spectrum.

If the light source is specially abundant in one colour—for example, almost all the light from neon advertising signs comes in a particular red colour—then the spectrum will be especially bright at the position which this colour occupies. If on the other hand one colour is missing, then the spectrum will be crossed by a dark line at the place where that colour should have appeared. As we shall see later, the spectra of the sun and stars do show such 'spectrum lines' and from them it is possible to deduce the chemical composition of the gases in the sun and stars.

The maximum information can be obtained when the spectrum is spread out as much as possible so as to reveal its finer details, and this may be done by passing the light through perhaps as many as half a dozen prisms in succession. Unfor-

tunately the number of prisms cannot be multiplied indefinitely, since, from a faint star, we receive so little light that we cannot afford to spread it out too much. The sun gives so much light that its spectrum can conveniently be spread out to an effective length of some hundreds of feet by the most powerful instruments, but the spectra of faint stars, even obtained with large telescopes may be only an inch or two in length.

So much for spectroscopy in general and the prism spectroscope in particular, but we have also seen that the fine, regularly spaced fibres of a delicate fabric can split light into its component colours. This process is imitated in spectroscopy by the use of a 'grating,' which often has the form of a very large number of fine parallel lines, (running in one direction only), ruled with a diamond on a glass plate. When light falls on a regular repeated structure of this kind, colours are seen; it is the fine regular structure of feather or wing which produces the brilliant colours of the peacock's plumage and of certain moths.

The effect arises because light is a wave phenomenon. There is one strange fact about waves of this kind: if two such wave-trains are added together they will reinforce one another if the crests of one wave-train fall on the crests of the other and will produce a wave of twice the depth. But if one wave-train is shifted so that the crests of one wave fall in the troughs of the other, the two waves will cancel one another, illustrating the strange fact that light added to light may give darkness. Now suppose light of one colour falls on a regular structure such as the ruled lines of the diffraction grating which may have ten thousand or more lines to each inch of its breadth. The light will be reflected from the very narrow strips of clear glass left between each pair of lines. It may happen that the light coming off in a particular direction from the top of one clear strip will lag just far enough behind the light coming from the next strip so that the troughs of one set of waves fall on the crests of the next, and so they cancel one another out. In fact, when we look at a diffraction grating we shall see colours, because in whatever direction we look, conditions will be just right to blot out some colour or other from the mixture which we know as white light. We shall see a succession of colours because the rays coming to our eye come at different angles

from different parts of the grating, so that from each part will come light from which a different colour has been knocked out. The grating can be used to produce a spectrum because the light reflected from it at different angles when the grating is illuminated by a beam of light, varies in colour according to the direction of the reflected rays. Gratings of various types are used in spectroscopy, but the discussion of the relative merits of prism spectroscopes and grating spectroscopes is a highly technical one.

The third example was the oil film which shows colours also by this 'wave-cancelling' or interference effect as it is called. Used oil dropped on water spreads into a thin film of minute thickness. Sunlight falls on it, and some is reflected from the top surface, while some goes into the oil film and is reflected from the lower surface. Again we have the situation in which there are two trains of waves one of which lags a little behind the other, and if the lag is of just the right amount the two wave-trains will knock each other out. The lag in this case is closely related to the thickness of the oil film, because one of the sets of waves has done the extra distance entailed in going down into the film and coming back up again. Actually when we see a red colour on the film the oil there has a thickness which is either 1/4, 3/4, 5/4 or some similar fraction of the wavelength of red light. If the colour is blue the thickness is a similar fraction of the wavelength of blue light, and so on. This effect is imitated in spectroscopy by a device known as the interferometer consisting of two accurately parallel plates of glass or quartz with air between. Its use is not to produce a spectrum but to measure wavelengths. In the case of the oil film the thickness could be deduced from the colour. In the interferometer the distance between the plates can be accurately measured and the wavelengths of light of various colours determined.

Since this book is concerned with the latest developments in astronomy we have omitted descriptions of older instruments, particularly those for the accurate determination of star positions. The most important of these is the transit circle, which is a telescope mounted so that it can only turn up and down in the north and south plane. Star positions are determined by timing the instants at which stars pass

across the field of such an instrument, i.e. by timing the moment at which the terrestrial observer is carried past the direction to any particular star. For a full description the reader is referred to standard works on astronomy.

Chapter Three

THE SOLAR SYSTEM

UNTIL comparatively recently, books on general astronomy devoted the greater part of their space to a description of the sun's system of planets. Historically these formed the subject of some of the earliest astronomical studies, but modern research has moved far beyond the confines of the solar system, which is now seen in its true perspective as a minute corner of the universe, offering little to the seeker after knowledge and nothing comparable to the rich harvest to be gained from stellar studies.

To include the solar system in our discussion is thus to break temporarily with our avowed object of surveying the frontiers of knowledge, but there are several reasons why it cannot be omitted entirely. In the first place, the planets, although so insignificant in themselves are close enough to form a striking adornment of our sky, and to gain the attention of even the most casual observer. A second, and more important reason is that our estimates of the distances of the stars are based, in the end, on the size of the solar system, and in particular on the distance of the earth from the sun, so that some reference must be made to the way in which the solar system is mapped out.

Lastly there are one or two interesting lines of astronomical investigation where advances are still being made, and to these must be added two problems, which, although of minor interest to the professional astronomer, have a strong appeal for the man in the street. The first is: 'Are any of the other planets habitable?' The second: 'How did the solar system come into being?'

The sun is a star similar to many others but it is either unique or very exceptional in that it has a number of planets which move round it in orbits, all of which are in roughly the same plane and moving in the same direction. This means that quite a good model of the solar system could be made on a table top, with all the planets moving on the surface of the table in orbits which are roughly circular, with the sun at the

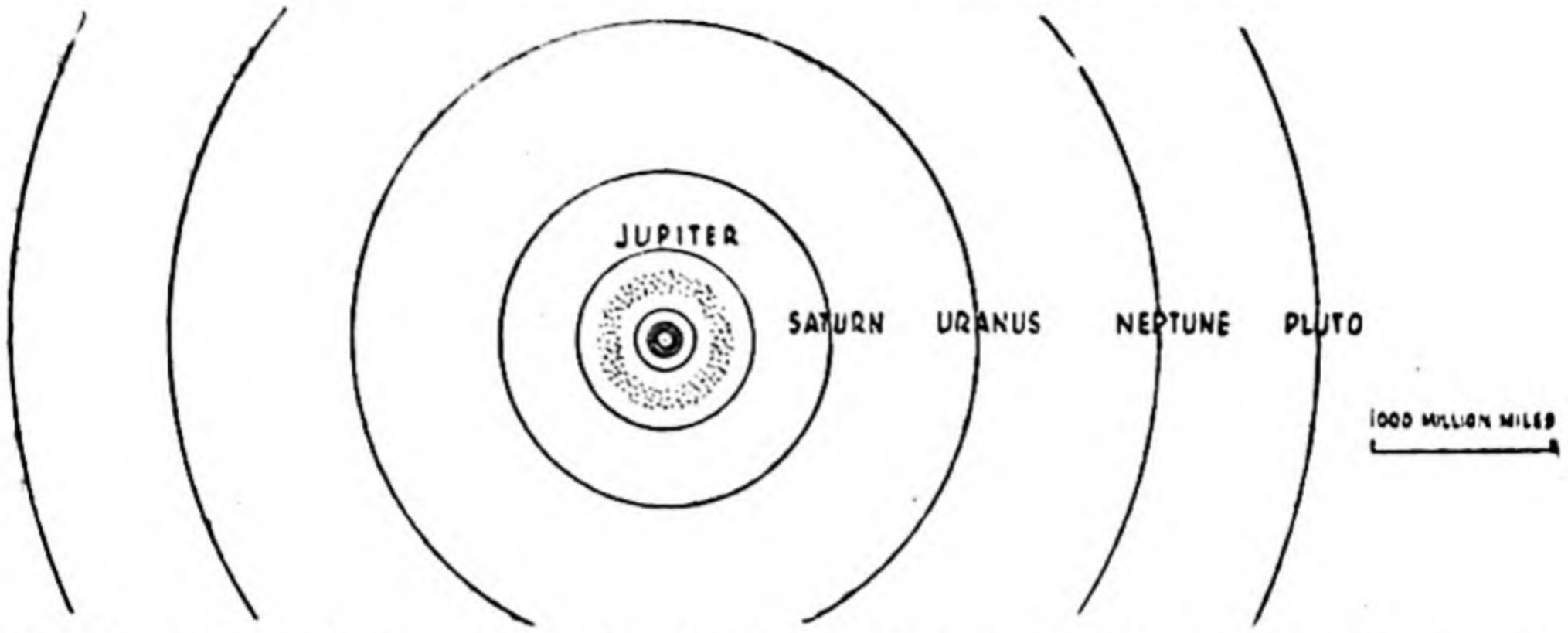
centre, and all of them going the same way round. To us, therefore, the sun and planets all appear to move in a narrow band, the ecliptic, running round the sky and defining the plane of the table-top in our model. The distances of the planets from the sun are most conveniently expressed in terms of the astronomical unit of 93,005,000 miles, which is the average distance of the earth from the sun. The innermost planet, Mercury, is at 0·39 of these units from the sun, and the outermost, Pluto at 39·60 units from the sun. The more remote a planet is, the slower it moves in its orbit, so that the time taken for a distant planet to complete its circuit is greater than that taken by a nearer one, not only because it has further to go, but because it is also going slower.

There are nine major planets, all of which are comparatively small solid bodies, the largest of which, Jupiter, with an average diameter of 86,500 miles is almost exactly one-tenth the size of the sun, whose diameter is 864,000 miles. None of these bodies have any heat of their own, with the exception of that which may be generated by radio-active minerals in their interiors, and they are visible only because they reflect part of the sunlight which falls on their surfaces. Almost all the matter in the universe is in the form of gas, either aggregated into stars or in the form of tenuous clouds, and most of the solid matter which has been detected is in the form of fine dust. The existence of comparatively large masses of solid material, such as we find in the planets, is thus a most rare phenomenon.

All the planets rotate on their axes, just as the earth does, the rotation periods being determined from the movement of markings on their surfaces, or by other methods. In the case of Mercury and Venus, which show no definite markings, the rotation period is uncertain and it is probable that both these planets keep the same face towards the sun, just as the moon does to the earth.

All the planets are held in their orbits by the gravitational attraction of the sun. Some of the planets have satellites or moons which move round the parent planet, being held in their orbits about it by the gravitational attraction of the parent planet. When this is the case it is possible to compare the attraction of the sun for the planet with that of the planet for its satellite, and so to find the mass of the planet. In a

Fig. 9. *THE SIZES OF THE PLANETARY ORBITS*



The planetary orbits are roughly circular and these circles are shown to scale. The sun is at the centre and the innermost circles represent the orbits of Mercury, Venus, Earth and Mars reading outwards. The dotted zone represents the region of the orbits of the minor planets, of which about 2,000 are known.

case where a planet has no moon it is possible to find its mass in some cases from the disturbances which its attraction produces in the orbits of other planets.

The numerical data for the planets and satellites are collected in the following tables:

TABLE II: PLANETARY DATA

Name	*Distance from Sun in astronomical units*	*Orbital period ('year')*	*Rotation period ('day')*	*Diameter miles*	*Mass (earth=1)*
Mercury	0·39	88·0 days	?88·0 days	3,200	0·037
Venus	0·72	225 days	?225 days	7,900	0·826
Earth	1·00	365·26 days	23h 56m	7,900	1·000
Mars	1·52	1·88 years	24h 37m	4,200	0·109
At various distances from the sun, between the orbits of Mars and Jupiter, lie the orbits of the minor planets, of which some 2,000 are known. The largest of these bodies is only a few hundred miles in diameter, while the smallest known are masses of rock only five or ten miles in diameter.					
Jupiter	5·20	11·86 years	9h 50m	89,000 * / 84,000	318·4
Saturn	9·54	29·46 years	10h 14m	75,000 * / 68,000	95·2
Uranus	19·19	84·02 years	10h 45m	33,000	14·6
Neptune	30·07	164·79 years	15h 48m	31,000	17·3
Pluto	39·60	249·17 years	?	?	?

Astronomical unit = 93,005,000 miles: Mass of Sun = 332000 × earth.

* Jupiter and Saturn are not spherical but are flattened at the poles. The larger figure in each case is the equatorial diameter; the smaller the polar diameter. The flattening of the earth is 27 miles.

TABLE III: THE SATELLITES

Planet	*Satellite*	*Distance from planet (miles)*	*Diameter (miles)*	*Period of revolution about planet (month)*		
				d	h	m
Earth	Moon	238,857	2,160	27	7	43
Mars	Phobos	5,800	?10		7	39
	Deimos	14,600	?5	1	6	18
Jupiter	V	112,600	?100		11	57
	Io	261,800	2,300	1	18	28
	Europa	416,600	2,000	3	13	14
	Ganymede	664,200	3,200	7	3	43
	Callisto	1,168,700	3,200	16	16	32
	VI	7,114,000	?100	250	16	
	X	7,192,000	?	254	5	
	VII	7,292,000	?40	260	1	
	XI*	14,027,000	?	692	12	
	VIII*	14,600,000	?40	739		
	IX*	15,000,000	?20	745		
Saturn	Ring system	44,500–85,000	—		—	
	Mimas	115,000	?400		22	37
	Enceladus	148,000	?500	1	8	53
	Tethys	183,000	?800	1	21	18
	Dione	234,000	?700	2	17	41
	Rhea	327,000	?1,100	4	12	25
	Titan	659,000	2,600	15	22	41
	Hyperion	930,000	?300	21	6	38
	Iapetus	2,210,000	?1,000	79	7	56
	Pheobe*	8,034,000	?200	550		
Uranus	Ariel†	119,000	?600	2	12	29
	Umbriel†	165,900	?400	4	3	28
	Titania†	272,000	?1,000	8	16	56
	Oberon†	364,000	?900	13	11	7
Neptune	Triton*	220,000	?3,000	5	21	3

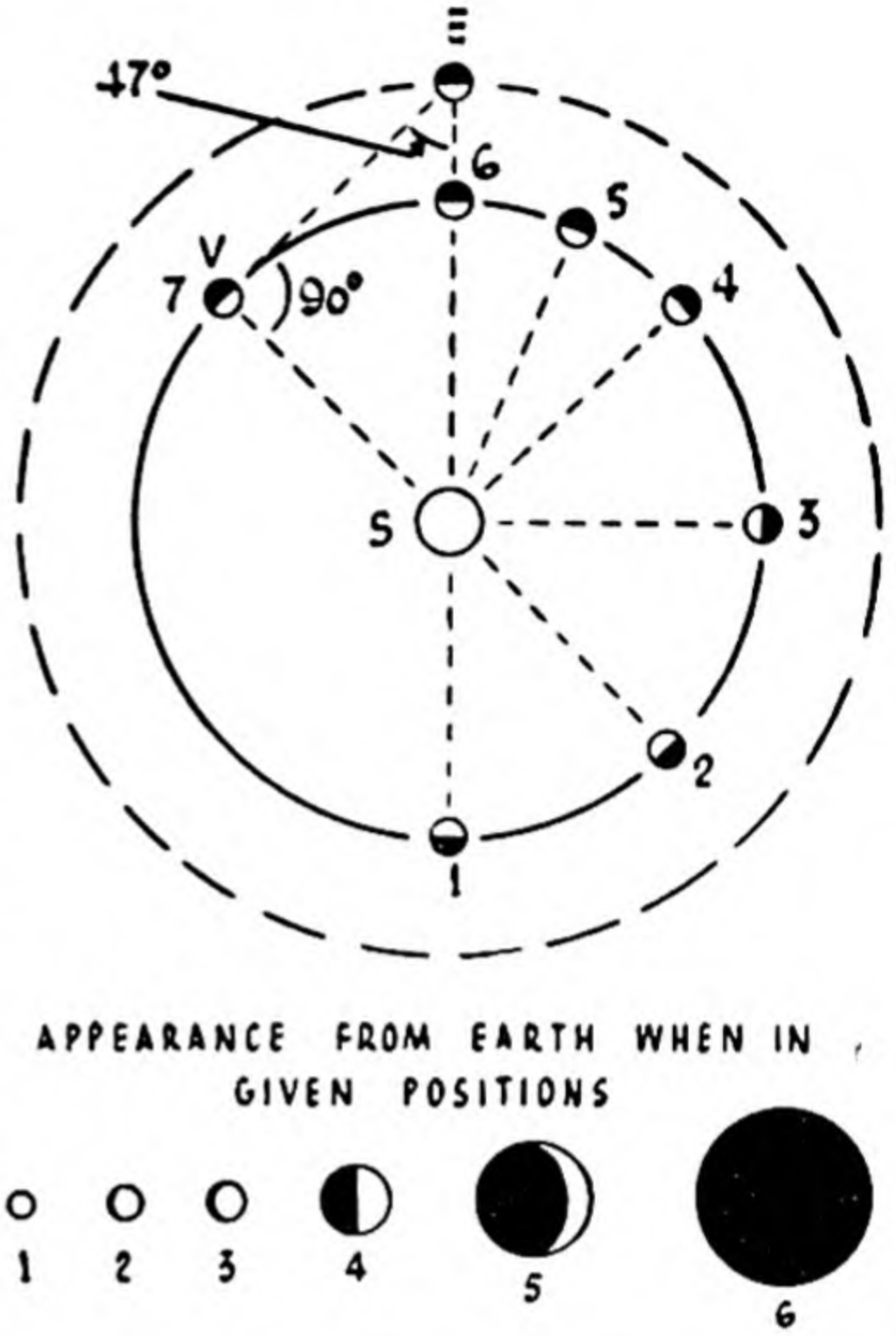
* These satellites revolve in a direction opposite to the general direction of rotation of the solar system and may be minor planets, which at some time in the past have been 'captured' by the parent planet and have continued to move round it as satellites.

† The orbits of the moons of Uranus are tipped at right angles to the plane of the table top model. We therefore are looking 'down' on them and see them as circles whereas all other satellite orbits are seen edge on and the moons appear to shuttle back and fore about their parent planet.

Fig. 10. THE PHASES OF VENUS

The relative sizes of the orbits of the earth (E) and Venus round the sun (S) are shown correctly. The sizes of the sun and planets are much exaggerated. Venus is shown in six positions relative to the earth. At 1 it presents its fully illuminated half to the earth, but its distance is large, and so it appears small as in 1 below. At position 4 it is comparatively close to the earth, and we see half each of the illuminated and dark sides of the planet.

The planet looks farthest from the sun as in position 7 when the lines VE and VS are at right angles. If the angle VES is then measured it is found to be about 47°, from which it can be deduced that Venus is 0·72 as far from the sun as the earth is. The actual distance in miles cannot be found unless we know the distance of the earth from the sun in miles.



Measuring the Solar System.

To show how the distances which are given in these tables can be determined we must consider how the solar system looks to us, and how we may deduce its size from various features of its appearance. It is comparatively easy to make a scale model of the solar system in which all distances are measured in astronomical units: it is very much more difficult to determine the length of the astronomical unit in miles.

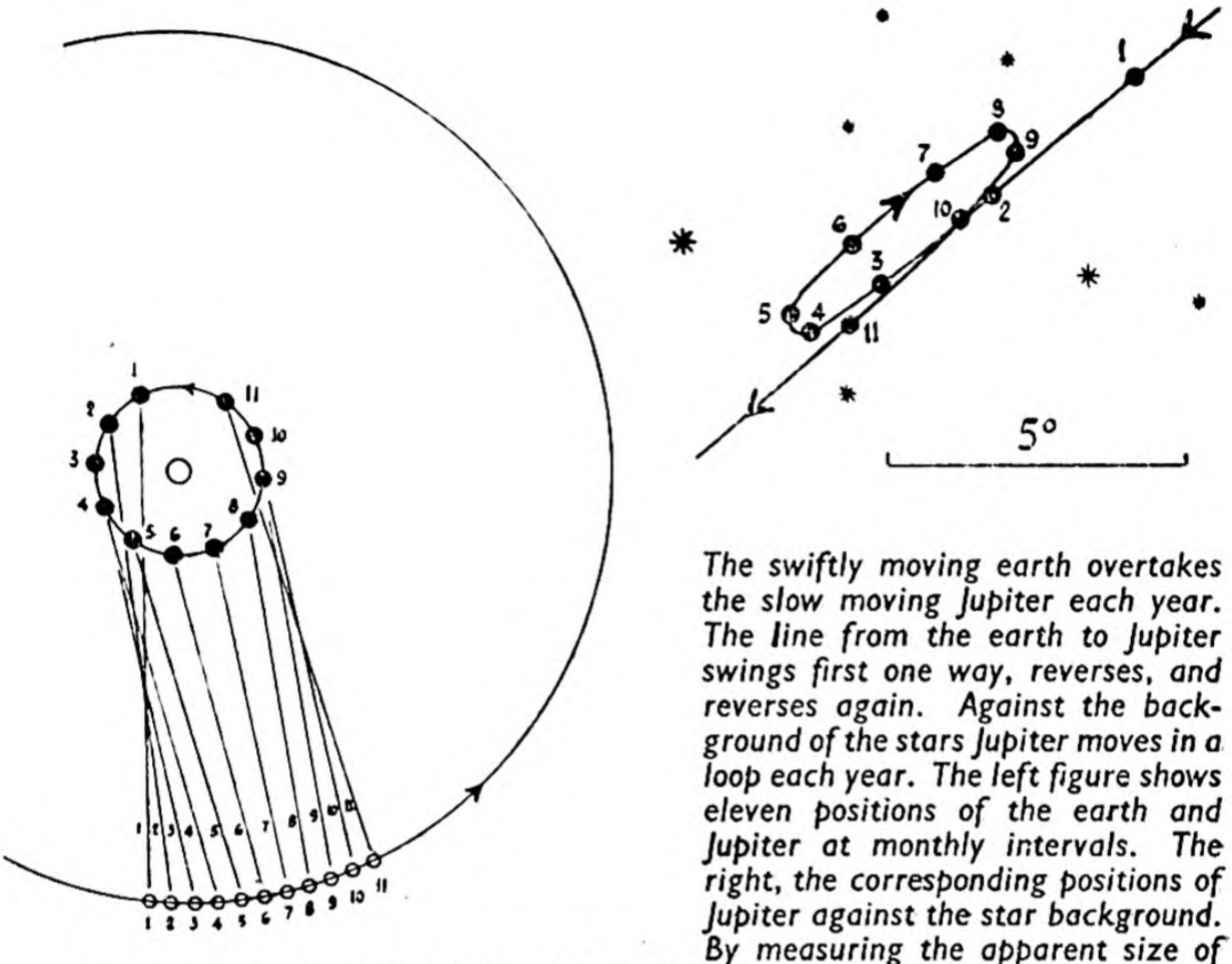
When we consider the movement of the planets as seen from the earth they fall into two classes: those nearer to the sun than the earth and those more distant. Venus and Mercury are both nearer the sun than we are. Sometimes they are on the opposite side of the sun; sometimes between ourselves and the sun, and sometimes to the east or west of it. We can describe the position of either of these planets by specifying the angle between the directions from us to the sun and to the planet. This angular distance will be greatest when the lines from the planet to the earth and to the sun are at right angles (see Fig. 10), and by measuring this maximum angular

distance from the sun it is possible to deduce the radii of the orbits of Venus and Mercury in astronomical units. The maximum angle for Venus is about 47° and for Mercury about 23° and from these the distances of 0·72 and 0·39 astronomical units respectively can be deduced. Since the earth turns through 360° on its axis in 24 hours (or 15° per hour) it follows that when Venus is west of the sun it never rises more than about 3 hours before the sun: whereas when it is east of the sun it never sets more than 3 hours after the sun. The corresponding time for Mercury is about $1\frac{1}{2}$ hours.

Since Venus and Mercury pass between us and the sun we can see part of the dark side of these planets, the proportion varying according to position. Hence when these planets are seen in the telescope they will show phases just as the moon does. When either of them is comparatively near to the line from the earth to the sun, and on the near side of the latter, then only a thin crescent of the illuminated half will be visible. When they are at their maximum angular distance from the sun they will be at 'first quarter' or 'last quarter' but will appear smaller because of their greater distance from us. When they are on the opposite side of the sun they will appear 'full' and smaller still. The orbits of Venus and Mercury are not exactly in the plane of the table-top model so that when these planets pass between us and the sun they do not usually cross in front of the sun's disc. In special circumstances these 'transits' do occur but they are very rare events: transits of Mercury occur about every 46 years. Transits of Venus occur in pairs, eight years apart, there being one pair about every 120 years.

The apparent motion of the outer planets is quite different and, since we are very close to the sun by comparison with them we only see their bright sides and they show no phases. All the outer planets take longer to circle the sun than we do, so that each year, as we come round to the same side of the sun as they, the earth overtakes them. The line joining the earth to, for instance, Jupiter, swings first, in our diagram (Fig. 11), anti-clockwise, then reverses its direction of motion. The earth then passes Jupiter, and a little later the line reverses its direction of motion again and swings anti-clockwise once more. The effect is that each year the path of each outer

Fig. 11. *THE MOTION OF JUPITER*



The swiftly moving earth overtakes the slow moving Jupiter each year. The line from the earth to Jupiter swings first one way, reverses, and reverses again. Against the background of the stars Jupiter moves in a loop each year. The left figure shows eleven positions of the earth and Jupiter at monthly intervals. The right, the corresponding positions of Jupiter against the star background. By measuring the apparent size of this loop it can be deduced that Jupiter is 5·2 times as far from the sun as the earth is. The distance in miles cannot be found until the distance of the earth from the sun in miles is known.

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planet executes a great loop against the background of the stars, and from the size of this loop it is possible to find the ratio of the distances from the sun of the planet and the earth, i.e. to find the distance of the planet from the sun in astronomical units.

When we know the distance of any planet which has a satellite then we can find the distance of the satellite from its parent planet in astronomical units. To find the maximum angular distance is a straightforward measurement, which gives us the angular radius of the satellite's orbit round its planet, and a knowledge of the distance of the planet from the earth at that moment, expressed in astronomical units, enables us to express the distance of the satellite in astronomical units. It is therefore little more than a problem of elementary geometry to find any distance in the solar system in astronomi-

cal units. In a similar way the diameter of the planets may be determined in astronomical units from the apparent sizes of their discs. To measure the astronomical unit in miles is much more difficult.

Finding the Astronomical Unit.

When a surveyor wishes to find the distance of some inaccessible object he measures out a baseline, and then sets up his theodolite at each end in turn. He measures the angles of the triangle formed by the two ends of his baseline and the inaccessible object and can then calculate the length of the sides of the triangle, i.e. he can calculate the distance of the object. This method breaks down when the object is very far away as compared with the length of the baseline because then the lines joining its ends to the inaccessible object are very nearly parallel.

The longest baseline available on the earth is only 7,900 miles even if the observations could be made from the north and south poles. It is impossible to find the distance of the sun (93,005,000 miles) with any accuracy from so short a baseline, and so some other, more convenient object must be found. In fact all we need to do is to find the distance of another planet in miles, and then, since its distance will already have been found in astronomical units by the methods sketched above, the length of the astronomical unit may be found.

However, the distances of all the major planets are too great for an accurate result to be obtained, and so a minor planet (see Table II), Eros, has been used, which about every thirty years approaches within about 15 million miles of the earth. The last close approach was in 1931 when an international programme of observations was organized under the direction of the present Astronomer Royal, Sir Harold Spencer Jones, and when, by an extension of ordinary surveying methods, the distance of Eros in miles was determined. The work was exceedingly complicated and involved many refinements, but the reduction of the observations was completed by 1941, yielding the value 93,005,000 miles with an uncertainty of only 9,000 miles. It was for this and other distinguished services to astronomy that Sir Harold received

his knighthood as well as the Gold Medal of the Royal Astronomical Society.

For stellar astronomy, this figure is the only fact about the solar system which we need to know, but in order to round off the discussion and to provide a basis for some remarks on the other problems mentioned at the beginning of the chapter we add some notes on the telescopic appearance and physical condition of the planets.

Notes on the Planets.

Mercury.

Visible to the naked eye, its maximum brightness being almost that of Sirius. Shows no definite surface markings. Is believed always to turn the same face to the sun. If this is so, the illuminated face must be at a temperature of something like 400° C., while the dark face must be extremely cold. The force of gravity on the planet is so small that it cannot retain an atmosphere.

Venus.

A very brilliant white object which can be as much as twelve times as bright as Sirius. The visible surface is probably the upper layers of a cloudy atmosphere and shows no very definite markings. The atmosphere of Venus contains no detectable proportion of either oxygen or water vapour. Venus may or may not keep the same face to the sun: a rotation period of thirty days has been suggested. The temperature on the dark side is about −25° C. which is higher than would be expected if the same part of the planet were always cut off from the heat of the sun.

The Earth and Moon.

The earth and moon are more like a double planet than a planet and satellite, the moon being, by comparison with its parent, but not absolutely, the biggest satellite in the solar system. The moon has no atmosphere and is covered with a large number of ring-shaped mountains, some of them as much as sixty miles across, which are believed to be composed of volcanic ash. Some of the mountain chains are

15,000 feet or more in height, there being no atmosphere to weather them down. The temperature on the moon rises very rapidly as each part passes into the sunlight, and falls again equally rapidly when once more covered by shadow. This is the result of the absence of an atmosphere which would blanket out these abrupt changes.

The earth is composed of a central core of nickel or iron rendered plastic by high temperature and pressure, extending to about 2,300 miles from the centre. Above this the density falls and there is a solid crust about fifty miles thick. This information has been derived from the study of the passage of earthquake waves through the earth.

Mars.

Under the most favourable circumstances Mars may be three times as bright as Sirius. Its surface is of a distinct red colour and shows a number of dark markings. The famous 'canals' linking these have never been photographed and are probably due to a well-known optical illusion. The polar regions of Mars show white, frozen polar caps which vary in size as the seasons of Mars succeed one another. Mars has an atmosphere but it is very tenuous, and contains certainly not more than one-sixth as much oxygen as the earth's and only five per cent as much water vapour. The polar caps are very cold at about −70° C. but on the equator at noon the temperature may rise to as much as 10° C. (Plate V).

The two satellites of Mars, discovered in 1877 are remarkable bodies. Phobos makes a circuit in a time less than the period of rotation of the planet, and so, to an observer on Mars would appear to rise in the west and set in the east. Deimos goes round only a little slower than the period of the planet's rotation and so would rise in the east, set in the west, remaining above the horizon for sixty-six hours at a time and going through its phases twice in this period.

The Minor Planets.

None of these are visible to the naked eye and all appear in the telescope as star-like points of light. Their nature is revealed by the fact that they move against the background of the stars, and they are discovered by long exposure photo-

graphy of regions of the ecliptic. The stars come out as points, but the minor planets give images which are lengthened into streaks by their movement. The largest are Ceres, 480 miles in diameter; Pallas, 304 miles; Vesta, 240 miles; and Juno, 120 miles. Eros is about 15 miles in diameter.

Jupiter.

When the earth passes closest to Jupiter its average apparent brightness is about twice that of Sirius. It is purplish white in colour and in the telescope is seen to be crossed by a number of dark bands rather reminiscent of the trade wind belts on meteorological maps of the earth. Occasionally markings appear on its surface and these enable the rotation period to be determined. The surface does not rotate as a solid body, the rotation at the equator being in a period of 9 h 50 m and elsewhere variable about an average of approximately 9 h 55 m. This, together with the marked flattening of the disc shows that the visible surface is not solid. The temperature is about –149° C. (cold enough to liquefy some gases) and the modern view is that Jupiter has a rocky core surrounded by immensely thick layers of ice above which comes a thick atmosphere almost on the point of liquefaction and containing such gases as methane and ammonia (Plate V).

Jupiter has eleven satellites. Four would be visible to the naked eye but for the glare of the planet and were discovered —the first objects to be discovered with a telescope—by Galileo in 1610. The rest are very faint and have been discovered photographically.

Saturn.

Saturn, visible to the naked eye as a point of light of a distinctly ruddy colour shows in the telescope a much flattened globe of a reddish colour on which markings of a whitish colour occasionally appear, surrounded by the famous system of rings. These reflect a considerable amount of sunlight, and the apparent brightness of the planet varies considerably according to the angle at which the ring system is tipped. At its brightest Saturn is about three times fainter than Sirius while when the earth passes Saturn with the rings displayed edge on, the planet is three and a half times fainter still.

From the size and mass of Saturn it can be deduced that the density of the globe is less than that of water, and this together with the marked flattening and the non-uniform rotation in different latitudes (compare Jupiter) shows that the visible surface is that of a cloud of vapour. The temperature is about −150° C. and so conditions must resemble those on Jupiter.

The ring system has a flat disc-like form, is certainly not more than ten miles thick (it is actually invisible when presented exactly edge-on), and extends from about 7,000 miles above the planet's equator to an outside diameter of 171,000 miles. The ring system consists of a vast number of tiny satellites, probably the remains of a moon, which, approaching too near Saturn was shattered by the strains imposed by the planet's gravitational attraction. Evidence for this is based on theory which shows that this disruption would occur at about the distance of the outer edge of the rings. Evidence for the particle nature of the rings is provided by theoretical analysis, by observations which show that the outer edge of the ring is moving slower than the inner (i.e. the rings do not rotate like a solid body but like the motion of the planets round the sun), and by the existence of a gap, or division in the rings, due to the fact that any particle moving in this gap would be violently disturbed and swept into another orbit by the gravitational action of Saturn's largest satellite, Titan (Plate V).

Uranus.

Uranus, just below naked-eye visibility, was discovered accidentally in 1781 by Sir William Herschel. The planet shows a greenish disc. It has four satellites whose orbital plane is tipped up so that they are seen to move in circles round the parent planet (see Table III).

Neptune.

Neptune was discovered as the result of calculations made independently by Leverrier and Adams who attributed disturbances of the motion of Uranus to an unknown planet. It was observed by Galle of Berlin in 1846 who recognized it as a planet, and simultaneously by Challis of Cambridge who

did not. Neptune receives only 1/900 of the light and heat from the sun that the earth receives, which would only suffice to keep it at a temperature of −222° C.

Pluto.

Pluto was discovered photographically in 1930. All available information is included in Table II.

Other occupants of the solar system include a fine dust-cloud from which the sunlight is scattered, producing a glow of faint light known as the Zodiacal Light. Fessenkoff, a Russian astronomer has recently advanced a theory to account for the existence of this dust cloud which must be continually renewed since it can be shown that dust particles are eventually dispersed by the radiation from the sun.

Small solid masses, usually not more than the size of a grain of sand, are frequently encountered by the earth in its orbit, and becoming luminous by reason of their swift passage through the atmosphere of the earth are seen as meteors, popularly miscalled 'shooting stars'. Occasionally much larger objects, sometimes as much as a few feet in diameter, and consisting mainly of iron are encountered which survive the passage through the atmosphere and strike the earth's surface.

Meteors are often encountered in groups which may be the débris of comets. Comets are small solid objects not more than a few miles in diameter, which, on approaching the sun are influenced by its radiation and emit tails of luminous gas, sometimes many millions of miles in length. The phenomenon is not similar to the luminous tail of a rocket, for a comet's tail always points away from the sun, i.e. roughly at right angles to its direction of motion. Some comets are periodic and return after a regular interval of some years. Others pay only one visit to the solar system.

Modern planetary research is chiefly concerned with problems of the constitution of the planets, being directed to the extension of the kind of information given in the planetary notes.

The problem of the habitability of planets hardly requires an answer if a careful study of the planetary information is

made. Life is maintained on earth because the temperature is equable, and because water-vapour and oxygen abound. We can at once rule out all the planets as abodes of life except perhaps Venus and Mars. Neither offers an agreeable home and we can certainly rule out the 'Men from Mars' of fiction and film. It is not so easy to rule out the possibility of rudimentary bacterial or vegetable life, but it is most improbable in view of the great age of the earth, presumably the same as that of the other planets, and the short time during which life has flourished here. Life of a rudimentary kind may have died out or not yet appeared on Venus or Mars: the probability of two planets being inhabited simultaneously is very slight indeed.

The problem of the origin of the solar system arouses a certain interest, and a variety of solutions have been suggested. None is perfectly satisfactory or above criticism, but the present view is that in the distant past the sun formed one of a pair of stars moving round one another in orbits under their mutual attraction. A star from outside the system, it is suggested, then passed close to the pair, and raised huge tides on their surfaces. Material torn from the sun's companion was captured by it, while the companion was captured by the intruder, and the two stars have long since become unidentifiable among the millions of known stars. The captured material which remained near the sun then condensed into the larger planets, and further encounters resulted in the formation of the smaller planets and the moon. It must be noted that the moon (like the smaller planets) can never have been gaseous, since, because it cannot now hold an atmosphere, it could not have held itself together if it had ever been a globe of gas. The probability of the sun passing near another star is about one chance in a million million during the next million years, but slender as this chance is, a catastrophic event of some kind must have occurred to produce the solar system.

For reasons such as this, the average astronomer a few years ago would have allowed himself to say fairly definitely that the solar system was unique, but it now seems as if this opinion may have to be modified. One of the stars nearest to our sun, the double star 61 Cygni, whose position has been carefully observed for some eighty years, shows irregularities of motion

which have been attributed by Dr. K. Aa. Strand to the presence of a planetary body about twelve times the mass of Jupiter moving under the attraction of the two stars. This hypothetical body emits no light of its own and cannot be seen directly. Its discovery is likely to be accepted by astronomers with some reserve, but, if verified, will have an important effect on our ideas of planetary formation.

As a final illustration of the fact that interplanetary distances are minute by comparison with even the smallest stellar distances, and that planets are extremely insignificant bodies we may make a rough calculation of the appearance of our own system from the nearest star. None of the planets would be directly visible, and the only indication of the presence of a planetary system would be the fact that the sun would appear at most 0·004″ (1/250 of a second of arc or the angular diameter of a halfpenny held up 750 miles away) out of its true position. If planetary systems are much more numerous than we believe, they will be almost undetectable by present methods of observation.

Chapter Four

ATTACK ON THE STARS

THE solar system is a rare local phenomenon which bulks so large in astronomy because it is so near. To extend our studies from the solar system to the system of the stars is to begin to think on a much larger scale in which a suitable foot-rule measures over two-hundred thousand times the length of the astronomical unit. We must adjust ourselves to a scale of time and space judged by which the solar system is insignificant in size—a mere appendage to one of many millions of stars; an oddity no more worthy of special discussion on this scale than the possession of a wooden leg is deemed to be a suitable subject for polite conversation.

But first we must prepare our attack. All our information comes to us on a ray of light. How best can we analyse that light so as to get the most information for our efforts? We can in fact split the possibilities of observation of a star up into three parts: we can observe its position: its brightness and its colour. We *cannot* observe its surface, except in one very special case, for we can never see a star as more than a point of light. We believe that all stars are globes of incandescent gas, but we cannot know this directly. If this assumption were incorrect we should only discover it if it led us into deductions which could be verified and were found to be untrue. There is no reason to doubt that stars are globes of gas, but although a matter of certitude it *is* an inference.

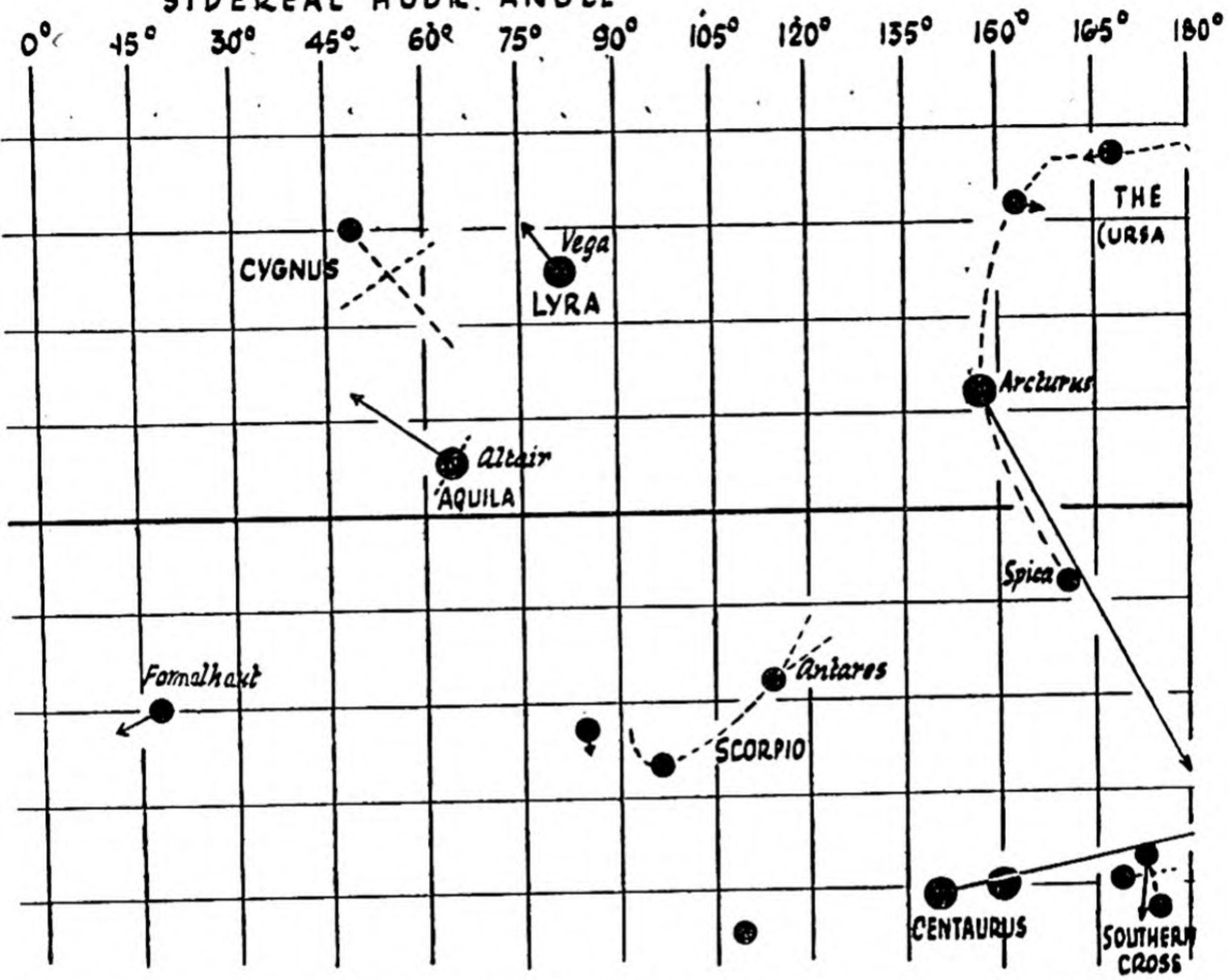
The things which we should like to know about stars: their diameters, temperatures, chemical composition, their real brightness (as distinct from their apparent brightness which is a compound of the real brightness and their distance from us), their masses and their positions in space: all these can be discovered in favourable cases but this knowledge must be got by roundabout routes. In other sciences we can measure the things we want to know. In astronomy we must make the best use of such information as we can piece together.

Let us now consider what information may be gleaned from the study of the position of a single star. There are considerable practical difficulties, but let us suppose that these have been overcome, and that we can measure accurately the changes of the position of a star in the sky.

These changes arise from two causes, the first and more obvious of which is that all the stars are in motion with speeds for which a convenient unit is miles or kilometres per second. Unless a star is moving directly towards or away from us, its position will change for this reason only. To begin to fix the scale of the stellar system let us note that even if a star were moving across our field of vision with the very low speed of one mile per second it would cover 30,000,000 miles in the year, but, even for the nearer stars, the shift produced by this movement would be far too small to be appreciated by the unaided eye. In fact, stellar distances are so great, that the shapes of the constellations have changed remarkably little even since ancient times. However such changes in position are taking place and are measurable, the change in position of a star in one year due to its own motion through space being called its *proper motion* and being expressed in seconds of arc. A proper motion of more than one second of arc per year is large (Fig. 12).

The second cause of change in the apparent position of a star is the fact that our observing telescopes are changing position as the earth moves in its annual journey round the sun. In the past, one of the reasons advanced for believing that the earth was the centre of the universe was that, if, in fact, the earth were moving, then the stars would appear to change their positions as this movement took place. Such movements do occur, but the largest shift due to this cause is less then two seconds of arc, and they are, therefore, measurable only by comparatively refined methods. The smallness of these shifts is due to the very great distances of the stars. To measure the size of the solar system a surveyor's base line on the earth was just sufficient. To measure the distances of the stars, the nearest of which are at hundreds of thousands of times the distance of the earth from the sun, a much longer baseline must be used, and this is provided by the diameter of the earth's orbit. In six months the earth changes position

Fig. 12. THE BRIGHTEST STARS IN THE SKY



The chart shows the forty-one brightest stars in the sky. The stars will move to the ends of the arrows in 100,000 years.

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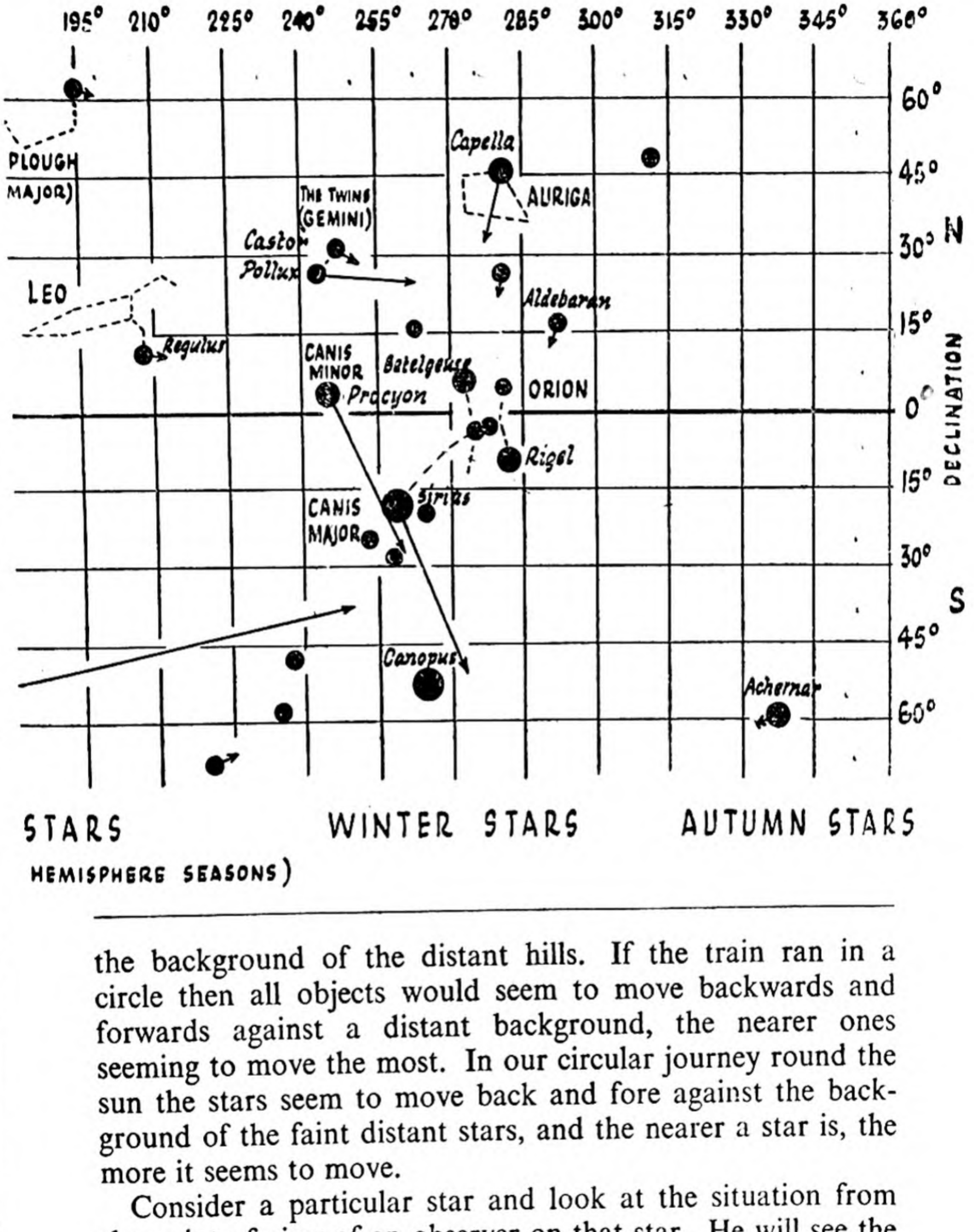
by 186,010,000 miles (2 astronomical units) and since all other distances in the universe are in the end based on this, it is easy to see why, in the last chapter, so much stress was laid on the accurate determination of the astronomical unit.

The apparent change in position of a star as seen from the two ends of the baseline provided by the diameter of the earth's orbit is the basis of the definition of star distances. From the window of a moving train, objects seem to be moving backwards: the telegraph poles seem to move faster than the trees in the middle distance while both move against

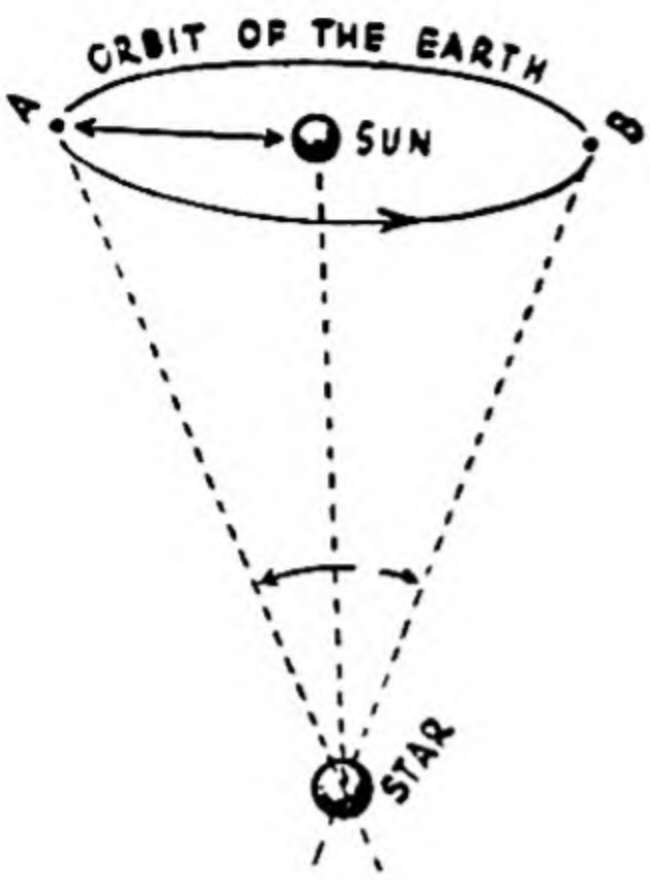
Fig. 12. THE BRIGHTEST STARS IN THE SKY

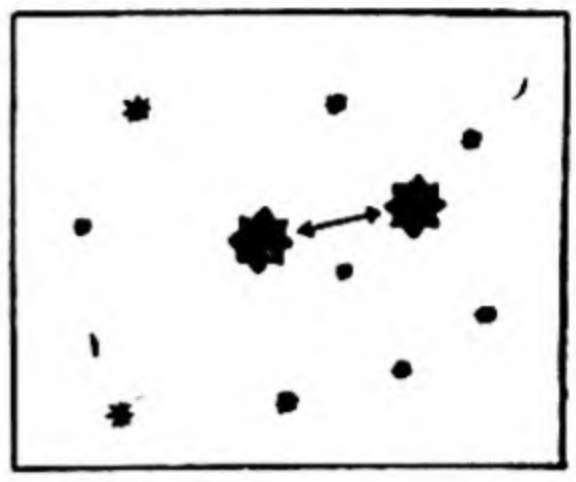


the background of the distant hills. If the train ran in a circle then all objects would seem to move backwards and forwards against a distant background, the nearer ones seeming to move the most. In our circular journey round the sun the stars seem to move back and fore against the background of the faint distant stars, and the nearer a star is, the more it seems to move.

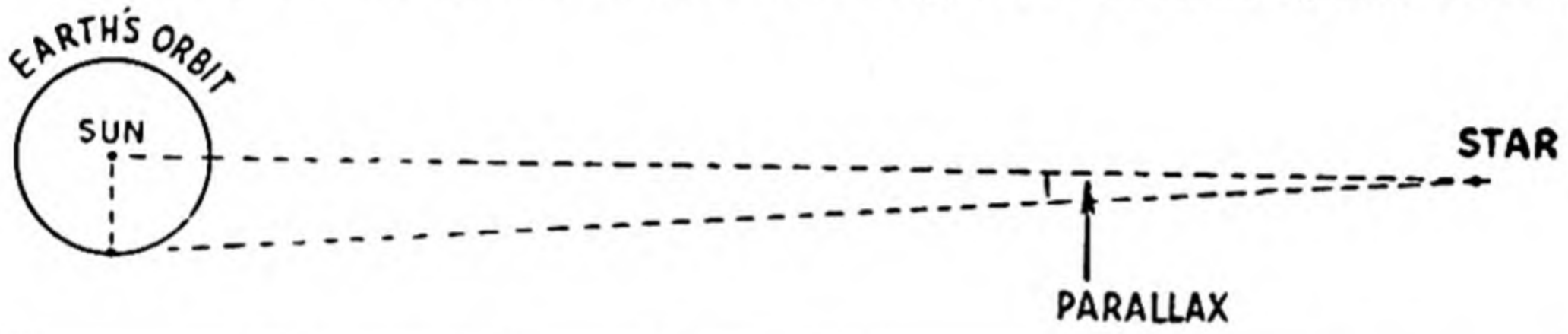
Consider a particular star and look at the situation from the point of view of an observer on that star. He will see the earth circling round the sun, and the angular diameter of the earth's orbit, as he sees it, is the same as the angular shift which the star makes when seen by us from opposite ends of

Fig. 13. THE DISTANCES OF THE STARS





As the earth moves round the sun, the lines from the earth to a star changes direction slightly. A and B are two positions of the earth separated by an interval of six months, and the known distance AB gives a base-line for determining the distance between the sun and the star. Photographs taken at an interval of six months show the nearer, brighter stars shifted against the background of the distant, faint stars. Astronomers describe the distance of a star by giving the 'parallax,' the angular size of a distance equal to the radius of the orbit of the heart as it would appear when viewed from the star.



our baseline. Half this shift gives the angular radius of the earth's orbit as seen by our imaginary observer and this angle is called the *parallax* of the star. When we specify the parallax of a star, we are, in fact saying how big the radius of the earth's orbit would look as seen from that star. As the earth moves round the sun each star appears to shift backwards and forwards against the background of distant stars through an angle equal to twice its parallax (Fig. 13).

To measure the parallax of a star, photographs are taken at intervals of six months and the amount by which that star has shifted against the background of the faint distant stars is measured. The parallax shift is mixed up with any proper motion which may be present, but the two can be disentangled because proper motion is a steady change of position, while parallax produces an oscillation. Thus, as far as parallax is concerned, there should be no shift in position on photographs taken a year apart, because the star is then being viewed from the same point of the earth's orbit, and so any change in this interval must be due to proper motion. We can then knock off from the shift observed in six months the proper motion for six months, which will leave the parallax shift by itself.

When we state the parallax of a star we say how big the radius of the earth's orbit would look to some one on the star, and this is equivalent to stating the distance of the star. It is, however, an indirect way. For example we could measure distances on the earth by planting a six-foot man at some convenient fixed point and then express the distance of any other place from the fixed point by saying how big the standard man looked as seen from that place. In this case, just as in the stellar case, it would be more convenient to state distances from the standard length in some suitable unit—miles or feet.

The best measuring unit for stellar distances is a new one, measuring 206,265 astronomical units, which is the distance of a star having a parallax of one second of arc. From this distance the observer would see the earth going round the sun in an orbit which measured two seconds of arc across. This distance is called a *parsec* and is equal to 19·16 million million miles or 30·84 million million kilometres. This unit is almost universally used by astronomers because it is directly related to the quantity which is measured. A parallax of one second of arc means a distance of one parsec: a parallax of half a second of arc means that to an observer on this star the earth's orbit would appear only half as big, i.e. the star must be twice as far away, at a distance of two parsecs. A parallax of one-tenth of a second means a distance of ten parsecs and so on.

A second unit sometimes used is the light-year which is a measure of *distance*. Light waves advance at 186,000 miles or 300,000 kilometres per second, and there are 31,560,000 seconds in a year. Light therefore covers 5·88 million million miles or 3·25 parsecs in a year, and this distance is one light-year.

The nearest star, the southern star, Proxima Centauri has a parallax of 0″·763, i.e. a distance of 1·3 parsecs or about 4 light years. The first star distance measured was that of 61 Cygni, by Bessel in 1837, the parallax being one-third of a second of arc. The direct method of measuring parallaxes breaks down at about 200 parsecs, since this involves the measurement of an angle of 1/200 of a second of arc (the angular diameter of a halfpenny 600 miles away) and this is so small that it is about equal to the uncertainty of measurement involved.

We have seen that the actual motion of a star through space produces a proper motion. Clearly if the actual speed of the

star across the observer's direction of view (its transverse velocity) is ten kilometres per second, the shift of position will be much bigger if the star is close than if it is distant. Putting the matter the other way round, if a star has a given proper motion, a much higher speed through space will be needed to produce this shift if the star is distant than if it is near, i.e. the greater the parallax the less speed will be needed to produce a proper motion shift of a given amount.

It is quite easy to prove that there is a simple relation between the transverse or cross speed in kilometres per second, which we call V, the parallax p, measured in seconds of arc, and the proper motion, μ, also in seconds of arc. It is

$$V = 4{\cdot}74\ \mu/p$$

and using this formula we can calculate the cross speed of any star whose parallax and proper motion are known.

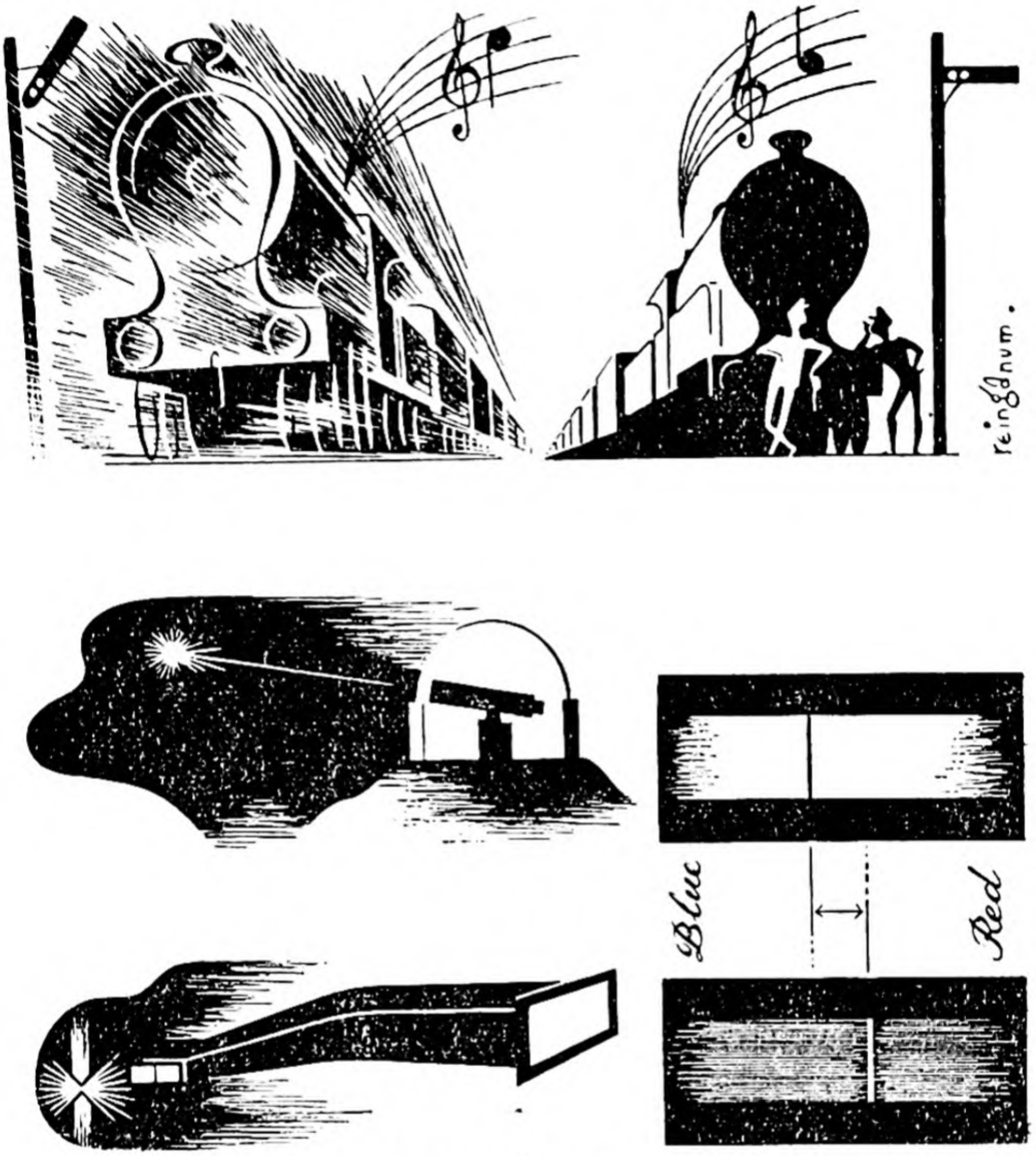
The Doppler Effect.

Motion directly towards or away from us produces no shift in position of the star and it might be thought that it would be impossible to find out how fast the star was moving in this way (its radial velocity). This measurement can be made using what is called the Doppler effect after its discoverer.

When an aircraft passes low overhead the engine noise sounds high-pitched as the plane approaches, then as it begins to move away, the noise suddenly drops in pitch. Similarly, if we are standing on a station platform and a train passes us blowing its whistle, there is a sudden drop in the pitch of the note at the moment when the train passes. It is a general rule that if a source of sound is approaching the note is sharper than it would be if the source were stationary, while, if the source is moving away the note is flat (Fig. 14).

The same is true of light waves. In sound, a high note means many air-vibrations per second: a low note, few vibrations. For light waves, many vibrations per second means a short wavelength: fewer vibrations a longer one. If the sound analogy is correct, then a light source moving rapidly towards us should appear of a higher pitch (i.e. more vibrations—a shorter wavelength—a *bluer* light) than if the source were not moving. Motion away from us should make the light appear redder. This is actually the case. If a light source is moving

Fig. 14. THE DOPPLER EFFECT



The pitch of the whistle of the approaching train sounds sharper than the whistle of the stationary train. The faster the train is approaching, the sharper (higher frequency) the note becomes.

The spectrum lines of an approaching star are shifted to the blue (shorter wavelength, higher frequency) as compared with the same spectrum lines produced by a stationary source in the laboratory. The shift is proportional to the velocity of approach: a shift of 1 per cent in wavelength to the blue (or red) means a velocity of approach (or recession) of 1 per cent of the velocity of light, i.e. 3,000 kilometres per second.

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towards us with a speed of say one hundredth of one per cent of the velocity of light i.e. 18·6 miles per second, then all the wavelengths in the light emitted by the source are reduced by one hundredth of one per cent. The actual measurement is

carried out on the spectrum of the light source: if it is approaching, all the lines in its spectrum (see Chapter II) are shifted slightly to the blue as compared with the wavelengths of the same lines produced in the laboratory. If the shift is to the red, then the source is moving away. By this method speeds of as little as one kilometre per second can be detected and measured.

TABLE IV

Name	*Magnitude*	*Parallax*	*Distance (parsecs)*	*Absolute Magnitude*	*Spectral Type*	*Speed (kms per sec.) Radial (from Doppler effect)*	*Transverse (from proper motion)*
Sirius	—1·58	0·386	2·6	1·4	A0	—8	16
Canopus	—0·86	0·014	71	—5·4	F0	+20	7
αCentauri (Rigel Kent)	0·06 { 0·33 / 1·70	0·768	1·3	4·6 { 4·8 / 6·2	G0 / K5	—22	23
Vega	0·14	0·121	8·3	0·6	A0	—14	14
Capella	0·21	0·078	13	—0·3	G0	+30	27
Arcturus	0·24	0·087	11·5	—0·3	K0	— 5	124
Rigel	0·34	0·006	167	—5·7	B8	+23	4
Procyon	0·48	0·315	3·2	3·0	F5	— 4	19
Achernar	0·60	0·046	22	—0·9	B5	+19	10
βCentauri	0·86	0·017	59	—3·1	B1	— 5	11
Altair	0·89	0·205	4·9	2·4	A5	—27	15
Betelgeuse	variable 0·5–1·1	0·012	83	—3·7	M0	+21	13
αCrucis	1·05 { 1·58 / 2·09	0·023	43	—2·0 { —1·4 / —0·9	B1 / B1	+ 7	10
Aldebaran	1·06	0·060	17	0·1	K5	+54	16
Pollux	1·21	0·105	9·5	1·2	K0	+ 4	28
Spica	1·21	0·018	55	—2·3	B2	+ 2	13
Antares	1·22 { 1·23 / 5·50	0·014	71	—3·3 { —3·3 / +1·0	M0 / A3	— 3	11
Fomalhaut	1·29	0·145	7·0	2·3	A3	+ 7	12
αCygni (Deneb)	1·33	0·005	200	—5·2	A2	— 4	2
Regulus	1·34	0·046	22	—0·2	B8	+ 3	25

α Centauri, α Crucis and Antares are double stars.

There are 146 stars in the sky brighter than magnitude 3·0: 41 brighter than magnitude 2·0: 12 brighter than magnitude 1·0, and 2 brighter than magnitude 0·0.

Positive radial speeds mean that the star is receding: negative that it is approaching.

In Table IV are listed the twenty brightest stars in the sky. The first column gives their names (many of them Arabic in origin). The second column 'magnitude' expresses their brightnesses, the term being explained below. Then comes parallax and the distance in parsecs deduced from it. 'Absolute magnitude' describes the real brightness of the star, not that brightness which it appears to have as the result of being at a particular distance from us. This also is explained below, and so is 'Spectral type' which describes the colour of the star. The radial speed is measured from the Doppler effect, and the transverse speed is calculated from the proper motion and parallax as already explained.

The Brightness of the Stars.

We must now consider the brightness of our star, which is the next measurable thing about it. In ordinary physics, sources of light are measured in terms of a standard candle. An electric-light bulb is rated at so many candle-power, and so on. For some uses a candle would be far too faint for astronomical purposes—for measuring the brightness of the sun, for instance—but for most uses the candle is far too bright. For instance the standard candle must be removed to a distance of a quarter of a mile before it looks as faint as Sirius—the brightest of the stars.

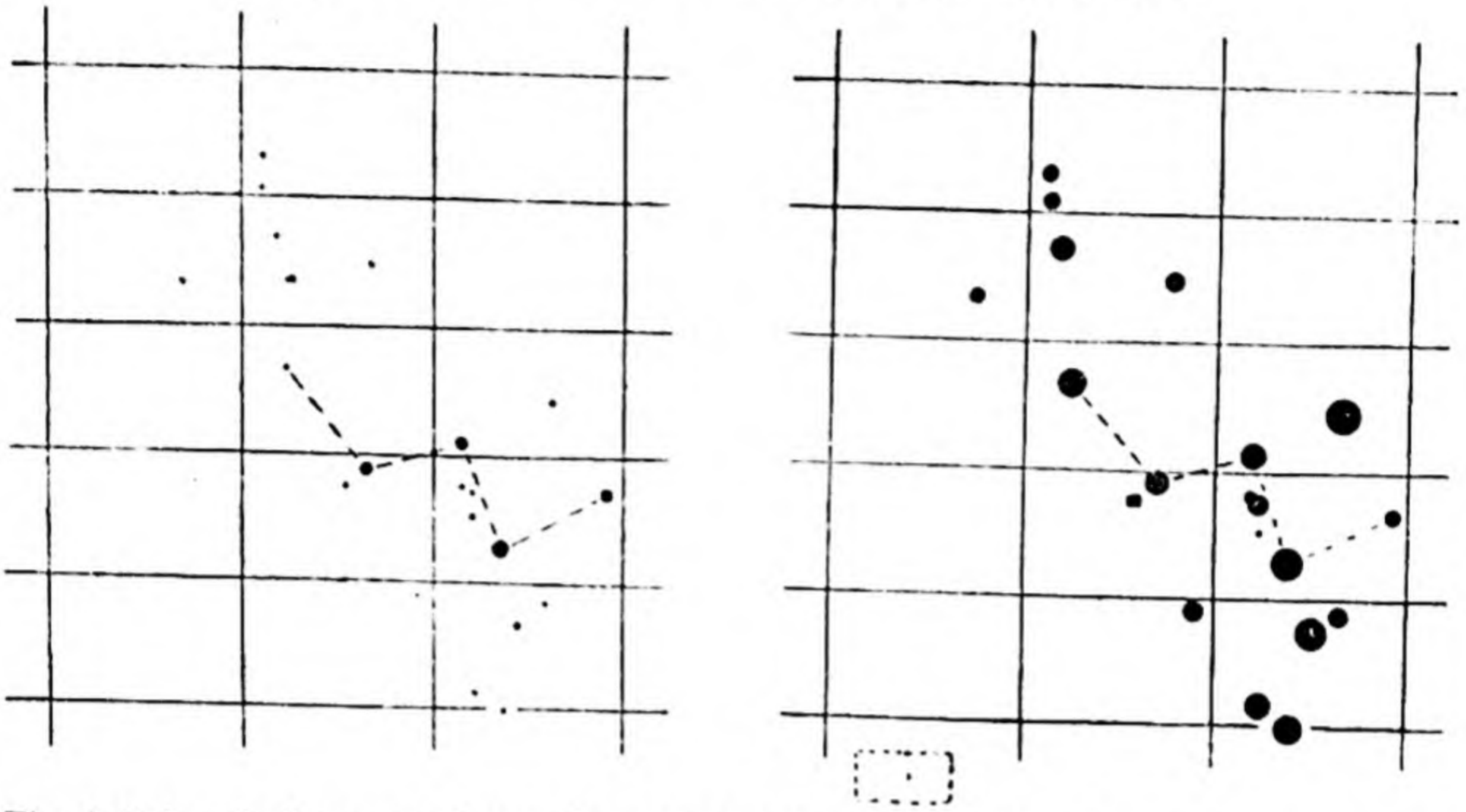
The classical method of stating the brightness of a star is that of assigning it a magnitude number. Hipparchus, who lived about 100 B.C. classified all the stars according to their brightness, and he divided them into six groups. All the stars which he knew were visible to the naked eye, and the brightest he called 'of the first magnitude': the faintest he described as being of the sixth magnitude, and there were four evenly spaced intermediate classes. Now for accuracy of measurement the human eye cannot compete with the best of modern instruments, but the trained eye is a light-measuring instrument (technically a photometer) which is not to be despised. Thus it came about, in the nineteenth century, when Hipparchus's system had to be replaced by something more accurate, that it was found that he had wrought better than he knew. There is one curious fact about the response of the eye to light. It is that the eye responds, not to equal differences of brightness, but to equal ratios. For example, a man seeing

two lamps at the end of the street could, with practice, tell quite accurately that one was, say, three-and-a-half times as bright as the other, but he could not tell the difference between them in candle-power. Another illustration is provided by an imaginary experiment in which one examines two rows of lamps. In one row the lamps have brightnesses of one, two, three, four, five, six, etc. candle-power. In the other they are of brightnesses one, two, four, eight, sixteen, etc. candle-power.

In the first row each lamp is a candle-power brighter than the one before. In the second row, each is twice the candle-power of the one before. A man looking at these two rows of lamps would say that the lamps in the first row were not equally spaced in brightness, and would say that they crowded together as one passed along the series. On the other hand, when he saw the second row he would say that they were equally spaced, and it would be the fact that his eye responded to equal ratios of brightness which would lead him to make this assertion.

So it was with Hipparchus and the stars. His 'magnitudes' turned out to represent equal ratios of brightness, the ratio between two magnitudes being about two-and-a-half to one. Thus we receive from a star of the first magnitude two-and-a-half times as much light as from a star of the second magnitude; a star of the third magnitude sends us two-and-a-half times less again, so that a star of the first magnitude is sending us $2{\cdot}5 \times 2{\cdot}5 = 6{\cdot}25$ times as much light as the third magnitude star. If we have two stars and we wish to find out how much more light one sends us than the other, all we have to do is to subtract the magnitudes and whatever that number is to multiply together so many factors of 2·5. The result is the number of times as much light received from the star with the smaller magnitude number, as is received from the one with the larger magnitude number. Hipparchus had six different magnitudes, so that there was a difference of five magnitudes between his brightest stars and his faintest stars, i.e. a ratio of $(2{\cdot}5)^5$ or 2·5 multiplied by itself five times, or almost exactly a hundred. The strict definition is based on the rule that a difference of five magnitudes is exactly the same as a ratio of one hundred to one in brightness, and this makes the ratio between two neighbouring magnitudes 2·512.

Fig. 15. THE REAL BRIGHTNESSES OF STARS



The left-hand diagram shows the constellation of Cassiopeia as we see it. The sizes of the dots indicate the apparent brightness of the stars. The right-hand diagram shows the brightness of the same stars if they were all at the same distance (ten parsecs) from us. Inset: the sun as it would appear from a distance of ten parsecs.

The faintest star visible to the naked eye has a magnitude of about six. Telescopic and photographic aid enable us to get down to magnitudes of over twenty. Compare two stars of magnitudes six and twenty-one. This is a difference of fifteen magnitudes, and each five steps correspond to a light ratio of one hundred to one. Thus fifteen steps correspond to a ratio in brightness of $100 \times 100 \times 100$ to one, or one million to one.

To fix the whole scale completely it is only necessary to fix the magnitude of one star, such as Vega at 0·14. What we are doing then is compare the brightness of all stars with that of Vega, either directly, or by a series of smaller and more easily measured steps. Of course, there are stars brighter than Vega, and the logical thing to do, since they are brighter, is to give them smaller magnitude numbers. Thus the two brightest stars, Sirius and Canopus have *negative* magnitude numbers, namely −1·58 and −0·86 respectively, while, at its brightest, Venus, for example has a magnitude of −4·3.

The full moon has a magnitude of −12·5 and the sun of −26·7, so that sunlight is about fourteen magnitudes or about four hundred thousand times brighter than full moonlight.

These are *apparent magnitudes* describing how bright the stars look to us. If a star were removed to twice its present distance, its real brightness remaining unchanged, it would become fainter by 1·5 magnitudes. Thus a star may look faint either because it really is faint or because it is very bright but also very distant. To compare the brightness of terrestrial light sources we put them at the same distance. To describe the real brightness of a star we must in imagination put it at a standard distance. The standard distance chosen is ten parsecs, and the magnitude which a star would have if placed at that distance is called its *absolute magnitude* and describes how much light the star is sending into space. The absolute magnitude of the sun is 4·85 so that, if placed at a distance of ten parsecs it would be comparatively faint. The absolute magnitudes of the twenty brightest stars in the sky are given in Table IV and figure 15 is a diagram of the constellation Cassiopeia as it looks to us, and as it would look if all the brighter stars were placed at a distance of ten parsecs.

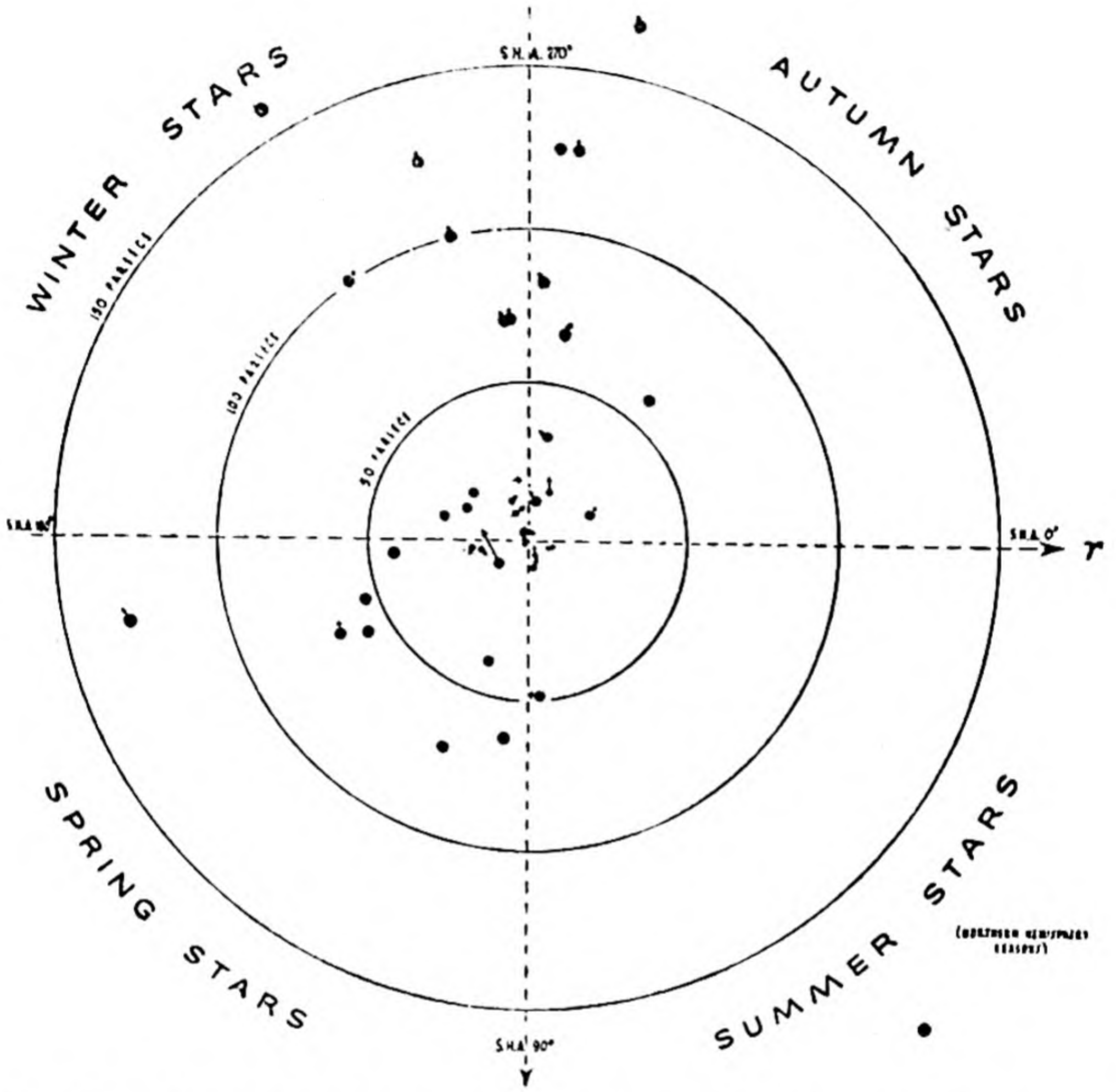
The real brightness of the stars varies very much between the brightest and the faintest. Canopus for example is 100,000 times as bright as the sun, and there are stars which are very many times brighter. The faintest stars, as we shall see are about 10,000 times as faint as the sun.

It is important to emphasize that differences in real brightness have a markedly selective effect on the stars which we can see. In Fig. 16 the real brightnesses and distances of the forty-one, apparently brightest, stars are plotted, and it looks as though all the distant stars are the brightest. This is not really so: in any volume of space there are both bright stars and faint stars, but the faint ones will be visible only if very close, whereas the bright ones will be visible at very great distances. Of the forty-one brightest stars in the sky, only four, Sirius, Procyon, Rigel Kent and Altair, are within five parsecs, whereas it is known that there are at least twenty-eight stars, most of them very faint, within this distance. Our selection of the brightest visible stars has given us far too many of the really bright stars, and far too few faint ones to serve as a good sample of the stars in space.

The Colours of the Stars.

The third immediately observable property of a star is its

Fig. 16. *THE REAL DISTANCES OF THE STARS*



The chart shows the real distances of the forty-one brightest stars in the sky. The sun is at the centre of the figure. Sidereal hour angle increases clockwise round the figure. Declinations cannot be represented on a flat diagram, and all distances are given as if the stars were at declination zero. The size of each dot represents the real brightness (absolute magnitude) of each star. The ones most distant from the sun are brightest because the stars selected are those which 'appear' brightest as seen from the earth, i.e. faint stars, even at moderate distances are omitted.

The stars will move to the ends of the arrows in 100,000 years. The preponderance of motions up the page is due to the fact that the sun is actually moving down in the direction of the large arrow, and hence the stars, in addition to their real motion, have an apparent motion up the page, just as objects seen from a moving train appear to be going backwards.

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colour, which is a rough-and-ready way of describing the light from a star. In the first place it only describes the very narrow range of wavelengths to which the eye is sensitive. Secondly,

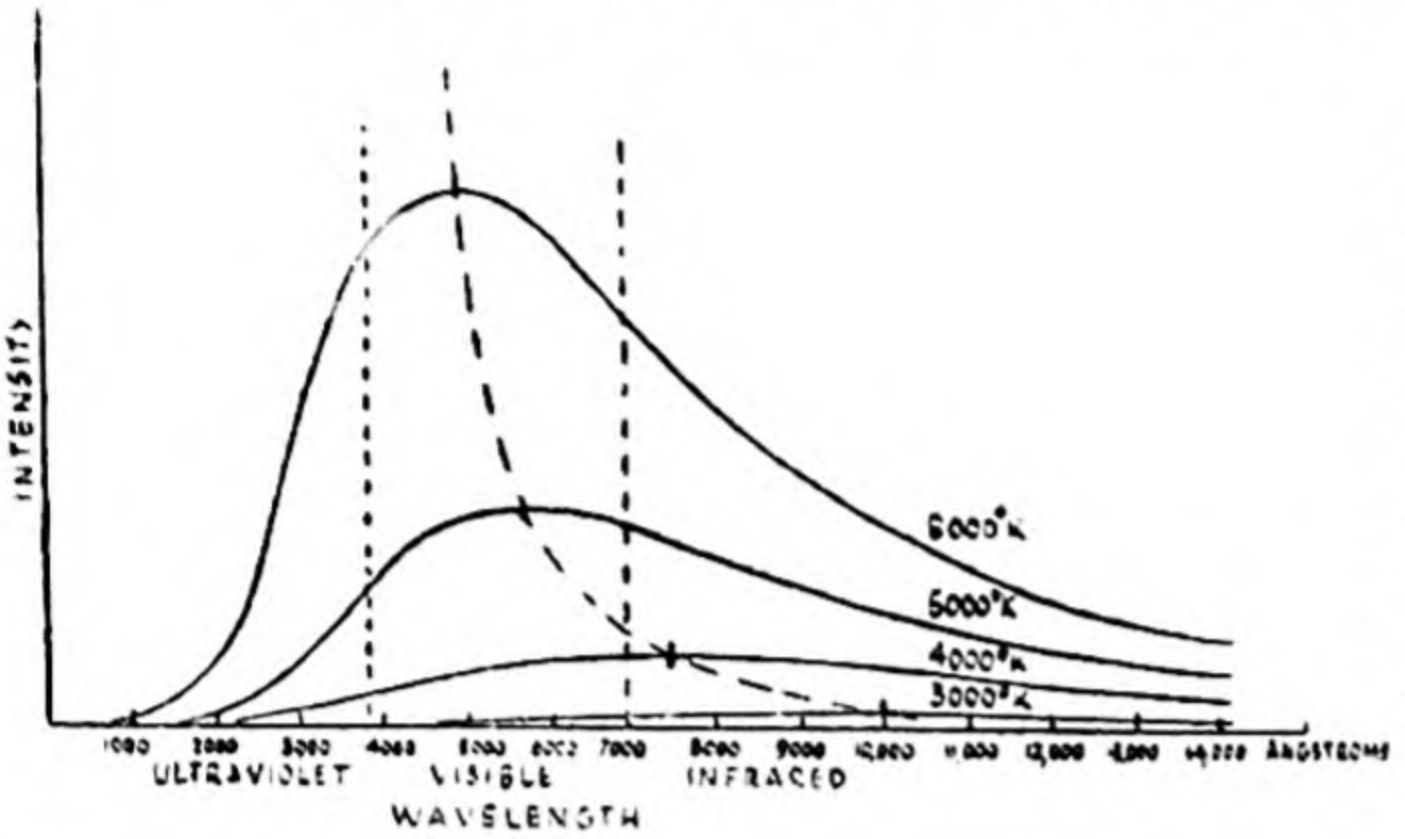
when a star is described as 'red' it does not mean that it emits nothing but red light. Even a red star emits some blue light; a blue or white star emits a considerable proportion of its light in the red. We must therefore begin by considering the way in which hot bodies emit radiation in all the visible colours and in the other wavelengths outside the visible range —the infra-red and the ultra-violet.

It is a matter of common experience that a body such as a piece of iron becomes whiter as it is heated to higher and higher temperatures. At first it glows a very dull red, but if the hand is held near it the heat rays or infra-red rays can easily be felt on the skin. This means that although a little of the radiation is in the visible range, the greater part is in much longer, invisible wavelengths. If the temperature is raised, the whole iron becomes both brighter and more white in colour. These characteristics hold quite generally. Under certain conditions it is possible to state quite general laws which are satisfied by radiation from hot bodies. When these laws hold the body is called 'black' and the radiation is known as black-body radiation. This name is used because radiation of this type is only emitted from bodies which absorb all light which falls on them. If this condition holds the radiation is independent of the chemical nature of the hot body.

One naturally thinks of a body which absorbs all the light falling on it as being blackened—covered with a layer of soot, or something of the kind, but the result can be achieved in a way which looks like cheating. If one takes a piece of material and makes a hollow in it which only communicates with the outside world by means of a narrow tunnel, then any ray of light which gets in down the tunnel will be reflected on the walls of the cavity and have only a very small chance of getting out again. That is to say that such an enclosure or cavity is an almost perfect absorber of radiation falling on it. It follows that if the cavity is heated, then radiation which escapes out of the small hole will be of the black-body type, which is, for this reason, often known as cavity radiation.

Many people find it difficult to believe that radiation of this type must be independent of the chemical substances which emit it, but this property of a small heated cavity can be tested very easily in the case of an ordinary coal fire. Often the heart

Fig. 17. THE RADIATION FROM BLACK BODIES



The hotter the body, the more radiation it emits, and the shorter the wavelength in which the radiation is emitted. The dotted curve shows the wavelength of maximum intensity. The vertical lines the limits of sensitivity of the eye.

of the fire consists of a small hollow almost completely enclosed by glowing coals, into which we can see through a small hole. When the fire is warming up and the cavity is illuminated by light from the room it is easy to see the surface details inside, but as soon as the fire is properly glowing and all the walls of the hollow are heated, it becomes impossible to distinguish any detail at all in it. The reason is that although coal is the most complex mixture of chemical substances, the fact that all substances emit the same cavity radiation means that all the details of the surface, seen by the light which they themselves emit, are equally illuminated: there are no shadows and no disturbance of the flow of radiation, and so we see nothing but a uniform glow—for how else, indeed, do we ever see detail in an object, except that it disturbs and breaks up the light which falls on it, these disturbed waves entering our eyes and causing nervous effects which we call seeing?

As we have seen, the hotter a body the more it radiates, and the whiter the radiation which it emits. These two ideas have been given precise form in the laws of radiation which are illustrated in figure 17. The curves show the relative quantities of radiation of different colours which are emitted by bodies at various temperatures. First of all, let us consider the total area of one of these curves, which represents the total energy radiated by say, each square centimetre of surface of a body at the given temperature. This increases very rapidly indeed as the temperature goes up. At a temperature of 500° C. a body is emitting no less than eighteen times as much energy altogether as a body at the temperature of boiling

water. To get a proper understanding of the energy emitted by hot bodies we must use a slightly different temperature scale from the ordinary centigrade one to which we are accustomed. The ordinary centigrade scale is marked off according to the temperatures of boiling water and melting ice. That is a useful way of looking at things on the earth, especially when we are dealing with water itself, but as we have seen, water, though common on earth, is one of the rarest substances in the universe. Is it to be expected that a scale of temperature based on a substance like water which by accident happens to be abundant on the earth, is going to be good enough for the study of the general laws of the universe? Naturally not. Now as far as we know there is no reason why, if we had the equipment, we could not go on raising the temperature of a body indefinitely. All we have to do is to keep putting in more energy. On the other hand, to lower the temperature of a body we have to extract energy from it. The heat energy of a body is due to the motions of the atoms and molecules of which it is composed, and, to put the matter very roughly, we can think of taking out more and more energy from a body until there is none left—until all the atoms and molecules are completely at rest. Things do not happen quite in this way, but the point is that there must come a stage when all the energy is removed, there is no more to be had, and we cannot lower the temperature any further. If we could do this we would have reached the lowest possible temperature, or absolute zero. Many experimenters have got quite close to absolute zero; they can never get right down because it gets more and more difficult the nearer one approaches to it, but we know that on the centigrade scale absolute zero comes at 273° C. below freezing. In all our discussions we use this absolute zero as a starting point for our temperature scale, and, for convenience we make the degrees absolute the same size as degrees centigrade. Thus ice melts at 273° absolute, and water boils at 373° absolute. This temperature scale is often called after Kelvin; the temperature, for instance, of boiling water being denoted as 373° K.

Now when we are discussing radiation from a hot body we are thinking about how much energy it emits, and when we think about absolute zero we are thinking about a tempera-

ture at which there is no more energy to be got out, so that it is not surprising that there is a relation between these two ideas. It turns out that the proper way to measure the temperature of hot bodies is in degrees absolute, and when this is done we arrive at an extremely simple result. It is that the radiation from unit area of the surface of a hot body is proportional to the fourth power of its absolute temperature. That means that if we want to calculate the total radiation of all colours coming from such a body, what we have to do is to find its temperature in degrees absolute, multiply that by itself three times and by a constant, and there is the result.

This is the basis of the statement made above that a body at 500° C. (773° K.) emits about eighteen times as much energy from each square centimetre of its surface as a similar body at 100° C. (373° K.). Actually, the ratio is:

$$(773)^4 : (373)^4 = 18{\cdot}4$$

Before going any further it is just as well to give the show away and to say that in fact most of the stars do emit radiation which is quite like black-body radiation in many ways (although there are important differences which cannot be discussed here), and one way of measuring the temperature of a star would be to find out how much radiation was emitted from each square centimetre of its surface. However, although the absolute magnitude tells us how much radiation is emitted by the whole surface of any star, we do not know how many square centimetres are sharing in the task, i.e. we do not know the sizes of the stars.

We can find out the temperature by considering first, not the total output of radiation from hot bodies, but its colour. Here our second law of radiation must be considered, which is illustrated by figure 17. On each curve we have marked the maximum point, and this tells us the favourite colour of radiation for each temperature. For instance a piece of matter like our own sun, which is at 5,000°–6,000° K. on the outside, radiates mostly in the yellow region. A star like Betelgeuse which is deep red in colour is at a temperature of 3,100° K. For the mathematically minded we will include the exact rule that the wavelength of maximum intensity multiplied by the absolute temperature is a constant. As we said, the sun at about 6,000° K. has a maximum in the yellow at

5,800 Ångstroms. A star at twice the temperature would radiate sixteen times as much from each square centimetre and the favourite wavelength would be half that of the sun, i.e. 2,900 Ångstroms which is a colour so blue that it has got outside our range of vision into the ultra-violet.

We can therefore determine the temperature of a star by determining its colour, provided that it radiates approximately like a black body. Various points are worth noting here. One is that these methods of temperature determination by the study of radiation are widely used in industry; in fact for most elevated temperatures—say above the melting-point of platinum at 1,773° C. (2,046° K.)—radiation methods are the only ones. The temperatures of furnace beds are regularly determined by the use of one form of optical device or another. Often the most convenient method here is not by observation of the colour but of the total radiation, but the basic principles rest on the radiation laws which were studied at first with a considerable emphasis on their astronomical applications.

The second point is that we are in effect determining the temperatures of stars as blue-hot, yellow-hot, red-hot, and so on, these designations corresponding to temperatures of round about 10,000, 6,000 and 3,000 degrees absolute respectively. However, a bar of iron looks red-hot when it is at a temperature of only a few hundred degrees, while the spectator who watches the stream of molten metal issuing from a furnace in an iron works would say that the metal was white-hot although its temperature is only 1,800° K. The essential point to remember is that we are concerned with the favourite wavelength at each temperature: a bar of iron already emits some red visible light when its favourite wavelength is still far in the infra-red. Again, it seems to be a peculiarity of the eye that if the whole field of vision is illuminated with light of one colour there is a tendency to refer all other colours to this dominant hue—if for example one remains in a room illuminated entirely by red light for any length of time one ceases to be conscious of it as red light, and on emerging from such a room true white light looks distinctly blue by comparison. This is what happens in the case of the furnace. The spectator standing close has everything he sees illuminated by brilliant red light whose real colour he cannot therefore

appreciate. From a considerable distance, however, the molten stream which looked so white is then seen in its true colour which is usually quite a deep red.

Yet another point is that the stars do not in fact look coloured when seen with the naked eye. To the trained eye Capella is a rich yellow like the sun, Betelgeuse is deep red and so on, but the casual observer receives these statements with some scepticism, and is frankly unconvinced when the colours of fainter stars are pointed out. There is a perfectly good reason for this. In the eye there are two sorts of seeing mechanism, one of which is used mainly for bright lights and is sensitive to different colours, while the other is used in faint illuminations and is not sensitive to colour. This effect has been known from time immemorial and is best enshrined in Boccaccio's remark that all cats look grey in the dark. In the same way all faint stars look grey, and colours can be distinguished with ease only in the brighter stars. It is quite easy to see for oneself that there are two sorts of seeing elements in the eye. The colour-sensitive ones are most numerous at the centre of the retina and are the ones used for seeing objects directly in front of the eye. The ones sensitive to dim light are mainly round the edge and would be used in seeing a faint object 'out of the corner of the eye.' Usually when we want to get a good look at an object we turn our eyes directly towards it, but it often happens that we cannot see a faint star directly in front whereas we can see it out of the corner of the eye. To test this, try looking straight ahead at some bright star one fine clear night and then without turning the eye, make a note of some faint star which you can see out of the corner. This, by the way, is a bit more difficult than it sounds—you have to turn your attention but not your eye. You will then find that your faint star may disappear when you turn your eye towards it.

This sort of consideration of vision under low illumination has of course occupied the attention of those concerned with night-fighter aircraft very closely during the past few years.

In concluding this chapter something may be said about the methods of determining the colours of the stars. The business is complicated by the fact that we cannot see all the light emitted by a star because our range of vision is limited,

and in addition most of the ultra-violet starlight is stopped because the layer of air in which we live absorbs it. So there is a sharp cut off on the blue side of the spectrum, and what is more insidious, some upsetting of the true proportions of energy which are coming to us in light of different colours. This is bad enough, but to make matters worse, infra-red radiation is very difficult to measure. Even in the very near infra-red, special photographic plates have to be used to register it, and further along the spectrum we come to a region where glass absorbs infra-red, so that our ordinary instruments built with glass optical components are no more transparent to infra-red than a sheet of armour plate is transparent to ordinary light. In the laboratory it is possible to observe this region with optical components made out of rock-salt, but they dissolve in water and crumble in damp and are very fragile, expensive and difficult to use. We may see advances soon because certain plastic materials which can be made into lenses and prisms are transparent to quite a long infra-red region, but hitherto progress here has been confined to certain very special cases.

What it boils down to is that we can observe a very small part of the radiation distribution from a star and we want to know, first of all whether it is part of a black-body curve, and if it is, of which one. For success, the observations have to be extraordinarily accurate, and they are extremely difficult to carry out. In the years 1926–32 a great deal of pioneer work on this problem was done at Greenwich. The optical parts of the instruments used absorbed some light of each colour, and the absorption for different colours was different. The air also absorbed different amounts of different colours, and its absorption varied from time to time. The observers —Greaves, Davidson and Martin—had to track down all these absorptions. Presumably the air and the instruments dealt the same with similar coloured light from two different stars, so comparison of one star with another was not too difficult. Then they compared a star with a lamp of known temperature—i.e. one giving known amounts of light of each colour—and they determined the air absorption by seeing what happened to the light of the lamp after it had gone through several hundred yards of air.

Their work is of first-class importance and gives us the first accurate information about the colours of the stars. Sufficient time has not yet elapsed for the full importance of this work which has since been duplicated by other observers to be realized, but it will undoubtedly have a profound influence on the future progress of astronomy.

In this chapter we have considered what direct observations may be made on a star: position, brightness and colour, and we have seen that they lead us to determinations of the distances, real brightnesses, motions and temperatures of the stars. There are many other things which we should like to know about stars and these can be arrived at by combining the trains of ideas which these three types of observation have started. In the next chapter we must first follow up in more detail the study of the colours of the stars, after which we can go on to discuss their chemical composition, sizes, masses and other properties.

Chapter Five

MORE ABOUT STARS

THE problem of determining the temperature of a star by measuring the light which it sends out in different colours is an extremely tricky one. The observer has, for example, to compare how much blue light there is with how much red light. Blue light and red light are absorbed differently in the earth's atmosphere: they are absorbed differently in the lenses and other components of the telescope and when they are finally recorded on the photographic plate there is the additional difficulty that a little blue light blackens the plate much more than a lot of red light. To assess all these differences accurately and to argue back to the amounts of radiation of each colour which the star, out in empty space, is emitting is a Herculean task and one not to be taken lightly.

However, there are other methods of assessing the temperature of a star, although it is now becoming clear that the temperatures estimated by these methods are slightly different from those assessed by the methods mentioned in the previous chapter. These differences are probably very important for understanding exactly how the star works. The use of the spectra of stars in sorting them out into classes of different temperatures is much older than the determination of their temperatures by their colour. This method is based on a knowledge of the behaviour of the properties of atoms, a field which we must now discuss briefly.

Atomic Behaviour and the Formation of Spectra.

The spectroscope spreads out the light from a source and arranges it according to its wavelength or colour. This gives a strip of coloured light ranging from red at one end to blue at the other. If any wavelength is missing there will be a dark line across this coloured strip at the position corresponding to that wavelength, and if light of any wavelength is particularly strong, then there will be a bright line at the appropriate place.

As we have already remarked in Chapter II the spectra (i.e. the strips of light) of the sun and stars do show such lines, and they are of first-class importance in the study of the stars. They can also be produced very easily in the laboratory. For example, if a pinch of ordinary salt is dropped in a flame it gives a bright yellow colour to it, and if this light is analysed by means of a spectroscope it will be found that all the light from this source is concentrated into two lines in the yellow part of the spectrum. These two lines are found to be characteristic of the metal sodium which is combined in the compound common salt, known chemically as sodium chloride. We now take a tube of glass and exhaust it and put a little of the metal sodium inside. If this tube is heated to about 200° C. so as to vaporize the sodium inside, and we then shine white light through it, the spectroscope will show that after passing through the tube the light has had two wavelengths abstracted from it, and that these two wavelengths coincide with those of the bright sodium lines in the first experiment. These two lines form, in fact, a sort of trade-mark of sodium. Take any substance or mixture of substances you please containing no more than one part in a million of sodium: put a bit of this substance into an electric arc and analyse the arc-light with a spectroscope, and there you will find these two lines betraying the presence of the metal sodium. The study of spectra originated in astronomical applications but, to-day, spectrographic analysis is a universal method of scientific investigation. It is used in chemistry, physics, medicine and even criminology: in industry, and in the universities: in almost every laboratory of whatever kind there is someone using a spectroscope. The reason for this is that all elements have their characteristic trade-marks which, under suitable circumstances they print on the light passing through their vapours, so that spectroscopy is an extremely important way of determining chemical compositions, a process of interest to all scientists. There are other and more complicated types of spectroscopy than this, but in astronomy we are mainly concerned with hot gases and vapours so that we need not concern ourselves with other developments.

Here we have a very fine powerful weapon of investigation.

Each element has its trade-mark and we learn what these trade-marks are by studying the spectra of elements in the laboratory. Then, having determined the wavelengths of the lines involved, we take spectra of the stars and see whether we can discover the trade-marks of the same elements there. Plate VI shows the trade-marks of some common chemical substances appearing in stellar spectra: hydrogen produces a series of lines in the visible region starting at the extreme red and working down through a series which is steadily more closely packed until they all bunch together at what is known as the 'head' of the series: sodium produces a very simple spectrum, but it has got other lines which turn up elsewhere, for example in the ultra-violet: iron has one of the most complicated spectra of all, containing several hundred lines in the visible region alone.

When we turn to the actual problem of the analysis of the spectrum of a star, such as, for example, the sun, things become a good deal more complicated. In the sun's spectrum something like 100,000 spectrum lines, showing dark on a bright background have been discovered and accurately measured, and almost all these have been identified.

If all lines looked exactly the same it would be a very difficult job to distinguish between them, for, with so many lines from all the elements, chance coincidence of some line with any selected wavelength is quite likely. The redeeming feature is that certain lines are stronger than others. For example, one of the pair of sodium lines is in general much stronger than the other, and, in the laboratory at any rate, the lines of the hydrogen series in the visible region get weaker and weaker along the series. This is a very important consideration in the interpretation of spectra. If the student of a spectrogram is faced with the identification of a given line, there may be half a dozen known spectrum lines falling very close to the given one. Some of these may be ruled out because an identification of the line as, say, due to iron, would require that there should be present a great many other iron lines as well, and this may not be so. But even if some of the possibilities can be excluded there may still remain a number of alternatives. The strength of the line is then a good guide: a particular trade-mark may show up very weakly in the spectrum due, for example, to the

fact that there is only a very little of the element responsible present in the source. If this is so, all the lines of the group should be weak, but within the group, there will be some which are naturally weaker than the rest, so that if the element is only present in minute quantity there should be a general scaling down of all the strength. Thus for example it would be wrong to identify a strong line as one of the later members of the hydrogen series, and to identify a weak line as one of the earlier members. On the whole the relative strengths of the lines are preserved, and all are scaled up or down together according to conditions.

The interpretation of a complex spectrum is thus a very arduous business and proceeds on a sort of detective system in which a consistent picture is gradually built up and all the lines identified.

Most stellar spectra consist of dark lines on a bright background, a case analogous to that of the passage of white light from a high temperature source through rather cool sodium vapour, and the modern picture of a star explains the production of this type of spectrum as due to the passage of the light from the deeper, hotter layers in the star through the relatively cooler outer layers of gas. What we are doing, in fact, when we analyse a spectrum is to study the light coming mainly from the outer layers of the star, and, when analysed, the spectrum will tell us whether any particular chemical element is present. It is tempting to use the words—'present or not' in this last sentence, but that is not quite true, and to understand why not we must consider in a little more detail how a spectrum is produced.

Why in fact are particular atoms capable of printing their trade-marks on the light? The answer is to be sought in the fact that all atoms of, say, sodium are constructed like all other sodium atoms. Each consists of a central heavy part or nucleus with a number of electrons moving around it in a way which may be very roughly compared with the movement of the planets around the sun. The comparison is, however, only a superficial one, for the electrons cannot move in any orbit which they choose—they may be thought of as bound to particular tracks which they cannot leave. They can, however, be switched suddenly from one track to another and this is

achieved when the atom absorbs light. The energy of the light is taken in by the atom and, as a result, an electron is suddenly switched to a new orbit. Later on it may switch itself back again of its own accord, and when this happens the absorbed energy is given up again. The interactions between light and matter are the subject of study of the quantum theory and they cannot be treated with any justice here. However, what the quantum theory says is that a jump of a particular size is only achieved when light of a particular wavelength is absorbed. Now all the atoms of sodium are similar: they all have the same prescribed orbits in which their electrons can run: they all have jumps of the same size from one orbit to another: and each particular jump is associated with light of a given colour.

If one sends white light, i.e. light including all colours, through some sodium vapour, the sodium atoms snap up light of just the colour to enable them to do their jumps. The colour which the sodium atoms are able to devour by reason of their peculiar construction is yellow light, or more exactly two closely neighbouring wavelengths in the yellow. We see, in fact, that sodium can remove just these wavelengths from the light because the sodium atom is constructed in such a way as to have an appetite for it. To explain why a sodium atom is constructed just so would require a whole book, but it is possible to calculate in advance almost all the special wavelengths which an atom will absorb once we know how it is constructed. We must leave the problem there at the deeper level of the theory of why atoms are constructed in this peculiar way. However, the acute reader will probably say, all right, we accept the fact that we shall have to read another Sigma book dealing with atomic structure before we can grasp exactly why atoms have a special appetite for radiation rather than a general one, but you said just now that later on the atoms disgorged their meal of radiation of their own accord. We see that the atoms take out radiation from the available supply, why doesn't the disgorging put it back again so as just to compensate exactly for everything that was originally taken away? In fact, we accept the statement that absorption of light prints the atom's trade mark on the light; why does not disgorging (or re-emission) rub the trade-mark

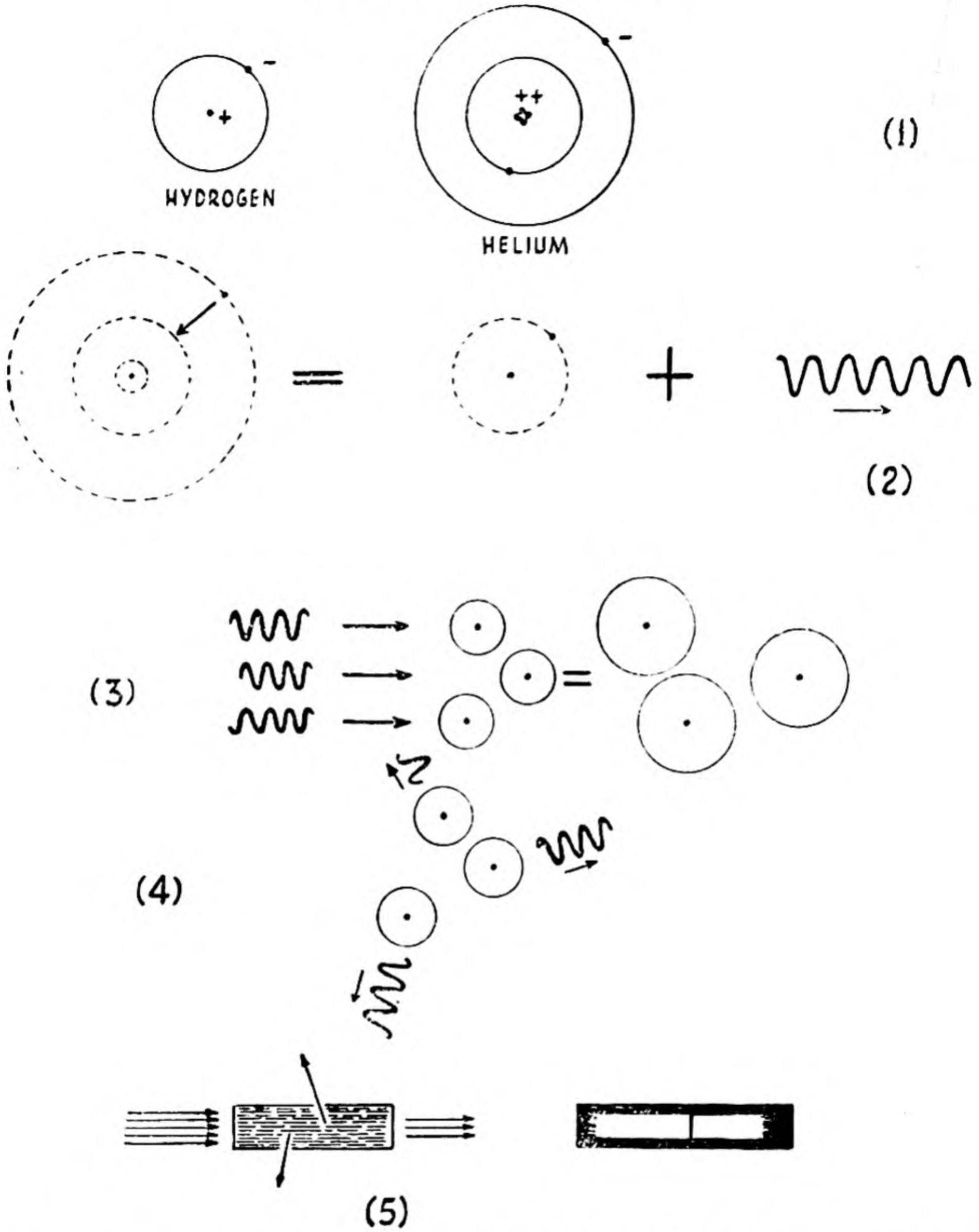
out again? The answer is that the absorption takes place from a stream of radiation flowing from the centre of the star outwards while the re-emission is in all directions (see Fig. 18). Hence there is, in the end, less radiation of the particular favourite wavelength in the outward-flowing beam, because the atoms have redistributed the light more uniformly in direction, and so a dark spectrum line appears.

Now although we can say that the presence of a particular trade-mark means that the element to which that trade-mark belongs is present in the source, we cannot say that absence of a trade-mark means absence of the element to which it belongs: or, more subtly, if a trade-mark is weak, we cannot say for certain that there is only a little of the element responsible for it. The key to the situation is our old friend temperature. A good analogy is provided by the case of a boiling kettle: if steam is coming out of the spout we know that there must be water in the kettle. If there is no steam, either there is no water, or the kettle is too cold. If the rules of the game prevent us from taking a look we can always decide by measuring the temperature of the kettle.

In just the same way, the trade-mark of a particular element may be absent from the spectrum of a star if the star is too cool or too hot. This happens particularly with hydrogen: we now know that hydrogen is the most abundant of all the elements in the stars, but it only shows a very weak trade-mark in the cooler stars. On the other hand too high a temperature can rub out the old trade-marks, for a very high temperature can so upset the atoms of some substances that they lose all their old trade-marks and get new ones. It is as if the atoms had been forced into liquidation and start new businesses in a disguised form under new trade-marks.

This is a fairly good analogy as we can see if we follow the process in detail. A gas is hot, or possesses heat energy because its atoms and molecules are in motion, and temperature is a way of expressing the violence of these motions. When more energy is put in, the temperature increases and the motions of the atoms become more violent. The increased violence of motion is shared by the electrons attached to the atoms, and at higher temperatures they make their jumps between different orbits more frequently, and so pass through

Fig. 18. ATOMIC STRUCTURE



Atoms consist of a central heavy, positively charged nucleus, round which are moving a number of electrons. These are negatively charged, and in a normal atom the number of electrons is just enough to balance the positive charge of the nucleus. (1) shows a hydrogen atom, the nucleus of which is called a proton, and an atom of helium with a nucleus consisting of two protons and two neutrons, the latter of the same mass as the proton but having no charge. The helium atom therefore has two electrons and has a mass four times that of hydrogen. All atomic nuclei can be thought of as built out of units of protons and neutrons.

The orbits in which the electrons move are restricted to certain definite sizes. When an electron jumps from one orbit to another nearer the nucleus, radiation

their hands more radiation in the particular wavelengths for which they have an appetite. But besides this special appetite atoms have a general appetite for radiation which they will only consume if the meal is big enough. A particular atom, such as hydrogen, will not consume a small meal unless it is just right for making its electron jump from one orbit to another. But occasionally a meal comes along which is very large: the atom absorbs it and suffers from violent indigestion, and its electron is knocked completely out of the atom. This is a process called ionization, and means the removal of an electron from an atom so that for a time the electron wanders about on the loose. However, when an atom loses an electron the bereaved one has one spare unit of electric attraction left, and can capture any wandering electron which comes too near. When the wandering electron is captured, it loses its surplus energy in the form of radiation—not in a particular wavelength but in a general one. There are thus really two sorts of process going on: jumps of electrons between orbits within the atom, which produce the characteristic trade-marks: and jumps right outside the atom and back again which produce a general radiation throughout the spectrum. This latter mechanism of radiation is the one which produces the general radiation discussed in the last chapter, and this process and the process of producing spectrum lines go hand in hand, both becoming more violent as the temperature is raised.

As the process of knocking out electrons, or ionization becomes more frequent, there will, at any moment, be a greater proportion of atoms of any given kind which have a

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of a definite wavelength or colour is emitted, (2). The reverse change can also take place, so that if radiation of the right wavelength is present an atom, say of hydrogen, can absorb some of it, its electron going into a larger orbit. Atoms therefore have a special appetite for radiation, the exact colours insisted on being characteristic of each chemical element.

In (3) a beam of radiation of the right wavelength is being absorbed by a group of atoms. In (4) it is being re-emitted, but this re-emission takes place not in the direction of the original beam, but in all directions at random. In (5) a beam of radiation is passing through a mass of gas (either in a tube in the laboratory or in the outer layers of a star). The absorbed radiation is re-emitted mainly sideways, and the beam coming out of the gas is reduced in intensity. If white light is used, and is passed through say, hydrogen, the special wavelengths of hydrogen will be reduced in intensity. The others will go through without being affected. A dark spectrum line will therefore be produced.

member of their electron family temporarily absent. Now an atom which is ionized will have a spectrum of its own, but the characteristic trade-mark of the remnant will not be the same as that of a complete atom. In fact, it may have a certain resemblance to the normal spectrum of some other element. Take for example helium, which has normally two electrons. When one of these is removed by ionization, the spectrum bears a certain resemblance to the normal spectrum of hydrogen. Ionized helium has a positive nucleus round which one electron is moving: hydrogen normally has one electron moving round a positive nucleus. The two nuclei are not the same, so that the spectra of the helium ion and normal hydrogen are not identical, but they do bear a close resemblance.

It follows then that we must learn the characteristic spectra not only of normal atoms, but of ions where the atoms have lost one, two, three or even more of their electrons. In addition, as the temperature of a star rises and a higher proportion of the atoms of a given element are ionized, the normal spectrum will fade out and be replaced by that of the ionized form of the element.

This complicates matters, but is also of great assistance to the investigator. Since ionization goes hand in hand with temperature, the astronomer can estimate the temperature of a star, not only by the difficult method of determining the total radiation of each colour which is emitted, but by the much simpler method of noting how far the spectra of normal atoms have been replaced by those of ionized elements—the progress of this replacement being calculable theoretically.

To summarize this discussion which has included a positively Irish mixture of metaphors and analogies we can say that the spectrum of a given mixture of gases changes with temperature: that these changes are fairly well understood and that the temperature can be fairly easily estimated by quite a superficial study of the spectrum.

Historically, of course, the development was just the reverse of our discussion. The properties of atoms were suggested by the study of spectra, and their faculty of printing their special trade-marks on light waves was known and used in identification before it was understood why this happened.

Even the new trade-marks which atoms acquire when they have lost one or more electrons were at least suspect long before it was known that this was the result of electron loss, or indeed before it was known that there were such things as electrons.

What the nineteenth-century investigators did was to take stellar spectra and to arrange them in some sort of order. This was a sort of astronomical botany—the first stage of any science. They were simply looking for regularities in their material. It was soon realized that red stars, yellow stars, and blue stars formed separate classes with recognizably different spectra, and these classes were denoted by the letters A, B, C, etc. Later developments have forced a rearrangement of these classes and the addition of new ones, and the splitting up of the main classes into decimal sub-divisions. The modern system of designation is by the letters, O, B, A, F, G, K, M, R, N, S with decimal sub-divisions and it represents on the whole a sequence of decreasing temperature. It is also a sequence in which the lines of hydrogen are prominent at first, reaching maximum strength at type A and then becoming fainter until at type G the most prominent lines are those due to metals.

TABLE V

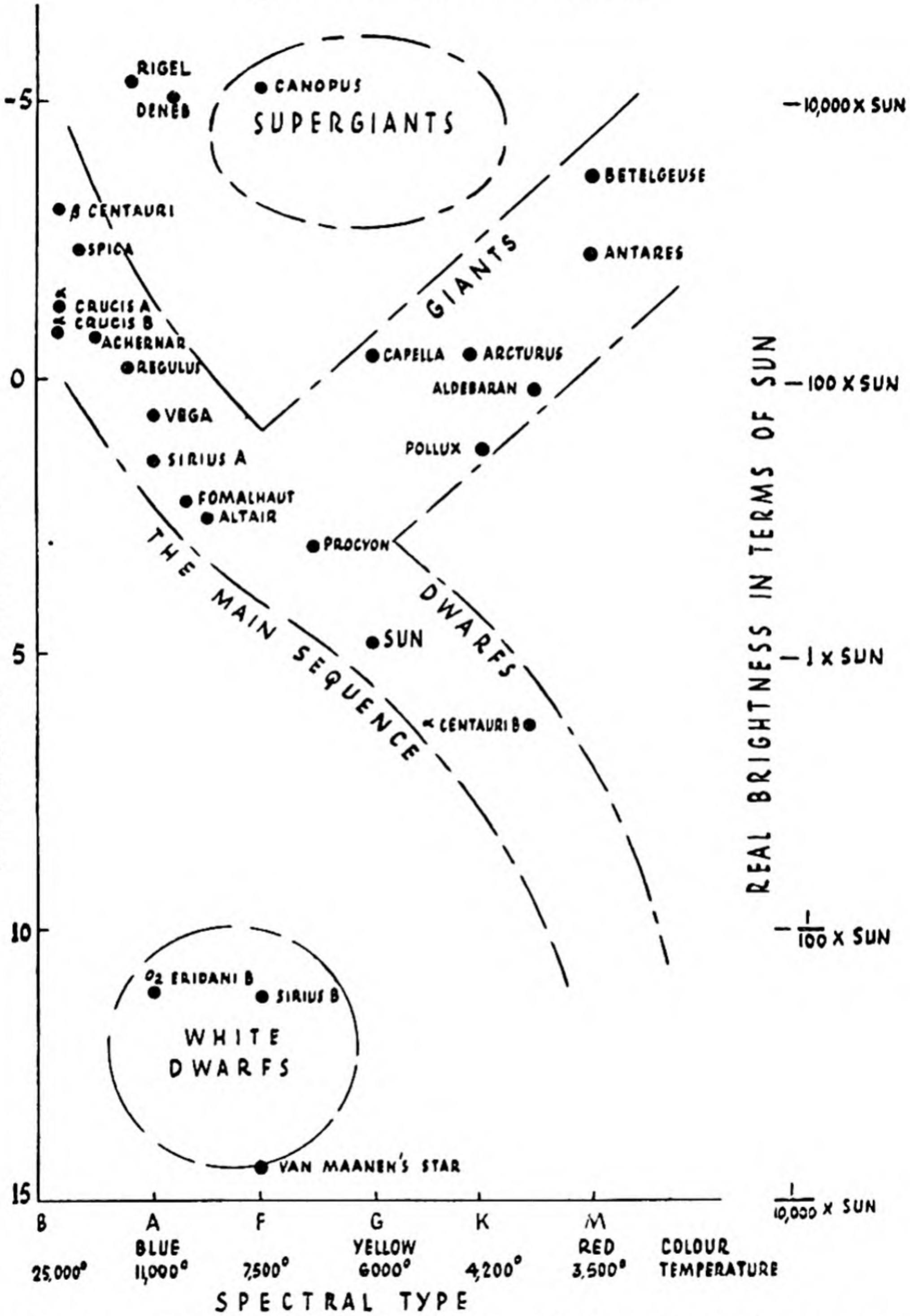
Star Temperatures and Spectral Types

Class	*Temperature (°K)*	
O	40,000	These temperatures are those of black-bodies emitting the same *total* radiation per unit area. They are called *effective temperatures* and may differ quite considerably from temperatures estimated in other ways, e.g. by considering the colour in which most radiation is emitted. The differences are important, but the subject is highly technical. The effective temperature of the sun, a G0 star is about 5,830°K. Spectral types for the brightest stars are given in Table IV p.62
B	20,000	
A	11,000	
F	7,500	
G	5,000	
K	4,200	
M	3,100	
R	3,000	
N	2,300	
S	13,000	

The easiest way to remember this sequence of types is by the mnemonic due to some unknown giant of astronomy, 'Oh, Be A Fine Girl Kiss Me Right Now. Smack!'

Classification is of little value unless it can be used to further understanding and this came when H. N. Russell, now doyen

Fig. 19. THE RUSSELL DIAGRAM



A diagram in which the real brightness of each star is plotted against its spectral type shows that the stars follow certain rules in their structure. The plotted points lie in the regions marked by dotted lines. A white, B-type, star must always be between 100 and 10,000 times as bright as the sun. A red, M-star is either several hundred times as bright as the sun or about a hundred times fainter than the sun. Some representative naked eye stars are plotted on the diagram.

of American astronomers, made the famous diagram which is named after him.

Russell's diagram is a sort of graph with the spectral types running across the bottom and the absolute magnitudes marked up the side (Fig. 19). We can put a dot on the diagram for each star whose absolute magnitude and spectral type are known—for example, Vega is spectral type A and has an absolute magnitude of 0·6. We just go on filling in dots and when we have put down all the stars for which we have information we take a look at the result. The dots do not fall just anywhere; they are gathered up into two bands. That means to say that if we want a red star of absolute magnitude +4 we should be disappointed. For some reason a star of this temperature and brightness cannot be constructed. You can have one with an absolute magnitude of about −1 (a giant 250 times as bright as the sun) or a faint one of absolute magnitude about +9 (a dwarf) 40 times as faint as the sun, but not one in between. This is not a sort of arbitrary outside rule; the explanation must lie within the star itself. A star is, in fact, a going concern which keeps going because its gravitational attraction for its various parts—which tends to make it collapse—is just balanced by other forces tending to keep it blown out. Our types really do tell us something essential about the economy of the star, and the diagram tells us that while for the hotter stars there is (with certain exceptions) only one possible size, for the lower-temperature stars there are two possibilities.

We can recognize the spectral type of a star by a quite superficial study of its spectrum, but there are other more subtle features such as slight differences in spectrum and temperature which enable us to decide whether a star is a giant or a dwarf. Thus we can tell that Capella is a yellow giant while the sun is a yellow dwarf, and it is distance alone which makes the really very much more luminous Capella seem relatively so faint.

We have now arrived at a stage where, by studying the spectrum of a star we can determine its spectral type, that is, we can estimate its temperature. We can also read off from the Russell diagram what its absolute magnitude is, and by comparing the absolute magnitude of the star with its apparent

magnitude we can estimate the distance of the star even beyond the 200 parsecs which can be measured directly by parallax determinations.

We speak rather of estimating distances, for in all astronomical measures—indeed in measurements of all kinds— a certain degree of error is inherent. However for short distances, say a foot or so, if we are reasonably careful we can be certain of making an error of less than about a tenth of an inch, that is, our error is less than one per cent. On the other hand even in estimating rather short astronomical distances, our methods of estimation are so indirect and involve so many assumptions that quite high errors are inherent in our results and must be accepted as part of the game. Thus for example, estimates of distances of stars up to a hundred parsecs are probably accurate to within about ten per cent. whereas for distances of a thousand parsecs we may cheerfully have to bear errors of thirty per cent or more, and for really large distances, we are glad if our answer is reasonably certain of lying between ten times the correct one and one tenth of the correct one. We would be very glad of more accurate methods but to ask for the same kind of accuracy in measuring astronomical distances that can be attained in measuring a yard of material is worse than crying for the moon.

We must always associate with each result which we obtain, either explicitly or by implication, some estimate of the uncertainty of the result. To lend point to this discussion let us come back to the Russell diagram. At the moment it contains all the stars within a couple of hundred parsecs of the sun, and these lie roughly on two strips instead of being scattered all over the diagram, and it is the width of these strips which produces the uncertainty. For example, it appears that an A star may have an absolute magnitude of anything from +3 to 0. Part of this variation may be due to observational error, but a good deal is due to real differences of brightness between different stars of the same type. We have divided our stars into different breeds: small Aberdeens, insignificant Pekingeses, moderate-sized Irish setters, and huge Great Danes, but just as a small Great Dane may be smaller than a large Irish setter, so may a faint B star be less bright than a bright A star. However, when the Russell

diagram is used for estimating stellar distances it is assumed that all stars of the same type have the same real brightness, and, for instance, all A stars may be assigned to absolute magnitude 1·5. If the star happens to be a very bright specimen of the type, say absolute magnitude 0, then we shall estimate its distance at only half its true value, whereas, if it is a faint specimen of the type, and is really of absolute magnitude 3, we shall put it at twice its proper distance. The Russell diagram is thus more of a general guide to distance than a means of accurate estimation, and in parts of the diagram where the band of stars is three magnitudes wide, we may be in error by a factor as much as twice too great or too small in estimating star distances from it.

It is also much more useful for the bright stars than the faint. There is a limit to the faintness of a star whose spectrum, and hence spectral type, can be obtained, since we must have enough light to spread out into a spectrum which can be photographed. Suppose this limit is represented by stars of the tenth apparent magnitude. Consider a very faint star of *absolute* magnitude 10. We can only get its spectrum if its *apparent* magnitude is less than ten, i.e. if the star is within ten parsecs of the sun. On the other hand a star of absolute magnitude −5 only has an apparent magnitude of ten if it is 10,000 parsecs away. This means that if the stars were uniformly spaced and there were as many bright stars as faint, we could use the Russell diagram for measuring 1,000 million times as many bright stars as faint. In fact, just because of this property, studies of the stellar system are mainly made on the very bright stars, and they tend to bulk far larger in our studies than their true proportion. Probably in fact faint dwarf stars are far more numerous than the very bright stars.

But although the Russell diagram is of great value in estimating the absolute magnitudes of stars and hence in estimating their distances, the determination of distance is by no means the only, or even the most important use to which it may be put.

We already know a good deal about stars: we know their distances and temperatures: their spectra give an indication of the chemical composition of their outer layers: we can deduce, either from their parallaxes or from the Russell

diagram what their absolute magnitudes are. As yet, however, we do not know what the radii of stars may be, and the Russell diagram used in conjunction with the radiation laws helps us to make this determination.

The sun has a temperature of about 6,000° K., while Betelgeuse, an M0 star has about half this temperature. From the radiation laws we know therefore that each square centimetre of the surface of Betelgeuse sends out only $\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}$ or one-sixteenth as much radiation as each square centimetre of the sun. Now the absolute magnitude of Betelgeuse is $-3{\cdot}7$ while that of the sun is about 4·8 so that Betelgeuse is 8·5 magnitudes, or about 2,500 times as bright as the sun. Since Betelgeuse is so inefficient a radiator it must have many more square centimetres in its surface than the sun has if it is to have a total output so many times as great as the sun's. It must in fact have 16×2500 as many square centimetres in its surface, which means that it must be 200 times the diameter of the sun, or 170 million miles in diameter. This, however, is an underestimate and illustrates how the limitations of the colour sensitivity of our eyes may lead us astray. Betelgeuse's absolute magnitude of $-3{\cdot}7$ is a measure of the *visible* light which it emits. We want *all* the light including the invisible infra-red, and Betelgeuse sends us a great deal of this because its temperature is so low. We have to make a correction of about a magnitude to get the so-called *bolometric* magnitude expressing the quantity of radiation emitted in all colours, visible and invisible, and when we do this we find a diameter for Betelguese of 265,000,000 miles, i.e. Betelguese is so large that, if placed where our sun is, we should find ourselves inside. The calculation for Betelgeuse is a little uncertain because its radius is not constant. The radius varies and the amount of radiation emitted also varies. Before giving the results for some other stars we must refer to a direct method of measuring star diameters using an interferometer. In Chapter II various methods were discussed by which spectra may be produced, and reference was made to the phenomenon of interference. Briefly it is that light is a series of waves, which, under certain circumstances can be combined so that the troughs of one set of waves fall on the crests of another and the two sets cancel each other.

When a telescope forms an image of a star it produces, not a point of light, but a small circular blob, called a diffraction disc, surrounded by a number of fainter rings, separated by dark spaces (Fig. 3). This is due to interference between light waves coming from different parts of the objective. If the telescope is pointed at a double star, the two images will be distinguishable separately if they are just so far apart that the diffraction disc of one falls no nearer to the second than the first dark space in its ring system. This represents the limit of resolution of the telescope as normally used.

If now the aperture of the telescope be covered by a screen in which there are two holes lying on the same diameter of the object glass, the appearance of the diffraction disc of a single star is changed. It is now crossed by a number of dark bands, as if it were made out of a material with dark and light stripes. If the two holes in the screen are brought close together, the dark stripes separate further apart, though the size of the diffraction disc remains the same. Now suppose a double star is brought under observation, and suppose that the two stars are so close together that they could not be separated by the telescope as used normally. It may still be possible to measure their angular separation by the use of the device we have been discussing. Each star produces a disc crossed with dark stripes, and the two discs overlap, possibly almost completely. If the displacement of the discs is such that the dark stripes of one fall on the light stripes of the other, then what will be seen will be a single uniformly illuminated disc without stripes. This will only be true if the separation of the stripes is just equal to the displacement of the discs; but the separation of the stripes can be altered by separating or bringing closer together the holes in the screen. The procedure is thus to alter the separation of the holes until the fringes disappear. It is then possible to calculate the separation of the stars from the distance between the holes at which the disappearance takes place. By this means it is possible to secure twice the resolution obtainable by the normal use of the telescope.

Now consider a single star. No telescope at present in use will show the true disc of a star, although the new 200-inch telescope will show the discs of some of the nearer and bigger stars. However, a single star may be thought of as consisting

of two half stars close together, and the stellar interferometer described above can be used to measure the separation of these two semi-circular stars, i.e. it can, in some cases, be used to determine the angular diameters of stars. Calculation shows that even for the nearest and largest stars the separation of the holes needed to make the stripes disappear is something like ten feet. The method adopted was to mount two small mirrors on a beam, first 20 feet, and in a later version, 50 feet long, fixed across the top of the 100-inch telescope. The mirrors, which took the place of the holes in the screen, could be slid in and out along the beam, and the starlight reflected from them was caught on two fixed mirrors and fed into the telescope. In this arrangement the 'holes' can be separated to a distance greater than the diameter of the telescope. To make an observation the mirrors are moved apart until the stripes disappear, and from the measured separation the angular diameter of the star can be calculated.

In the following table some measured angular diameters of stars are given and these, together with the parallax, give the real diameters in miles. For comparison the diameters calculated from the radiation laws (taking into account the correction for invisible light) are also given.

TABLE VI

STAR DIAMETERS: NEARBY GIANTS WITH LARGE ANGULAR DIAMETERS

Name	*Angular diameter (measured with interferometer)*	*Corresponding linear diameter (miles)*	*Diameter (miles) Calculated from radiation laws*
Antares	0″·040	265,000,000	225,000,000
Arcturus	0″·020	21,500,000	22,000,000
Aldebaran	0″·020	31,000,000	30,000,000
Betelgeuse	0″·035 (variable)	271,000,000	265,000,000

The method of direct measurement of diameters by the interferometer is applicable in only a few cases, and in most of the others the method of calculation from the laws of radiation must be used. Some typical stellar diameters showing the fairly regular progression from type to type are shown in Fig. 20.

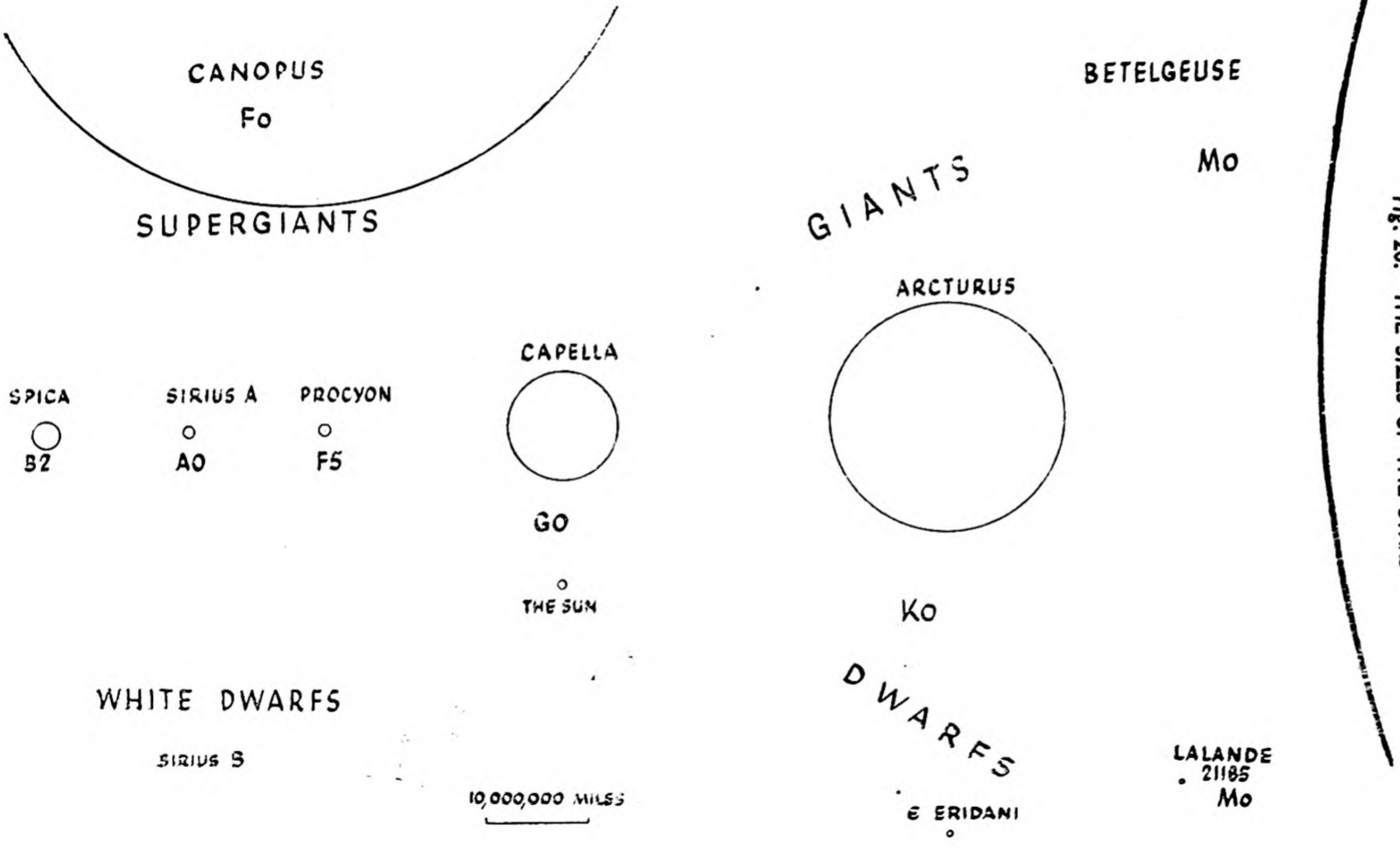


Fig. 20. THE SIZES OF THE STARS

There is, however, one other general case in which star radii may be found, but before we discuss it we must first say something about the measurement of the masses of the stars. It is not unusual to find that a star which, to the naked eye, or even in a small telescope, appears single, is actually a pair of stars moving round one another under their mutual attraction. Such a star pair is called a *binary*: when the stars are comparatively far apart they may be seen as separate stars which change position, possibly taking as long as a century or so to make a complete circuit round one another. In other cases, when the stars are very close and take only a few days or weeks to get round, it may be impossible to see them separately, but their binary nature is revealed by the fact that each star shows a spectrum. When star A is moving away, its spectrum lines will be displaced to the red by Doppler effect, while those of star B, which is approaching, will show a spectrum shift to the blue. The stars will then cross over; A will start moving towards us, and B away, so that now the Doppler shifts will be in the opposite directions. In fact, as the two stars go round and round one another, their spectra will shift rhythmically back and fore on top of one another.

If we can discover everything about the shape of the orbit and the speeds of the stars, we can calculate their masses. When we weigh an object on earth we measure the force of attraction which the earth exerts on it. We put it on a spring balance: the spring stretches: we know how much force stretches the spring a certain distance, and so we know the force with which the earth is attracting the object. In fact we balance the attractive force of the earth by the force of the spring.

Now what holds the two stars of the binary in their orbits? It is their attractive force for each other, and this force depends on the masses of the two stars. Why is such a force necessary? It is necessary to keep the stars moving in a curved path and to counteract the centrifugal force which would otherwise cause the stars to fly off at a tangent. But we can calculate this centrifugal force if we know how fast the stars are moving and how sharp a turn they are making as they go round in their orbits. Just as we balance the weight of a body on earth against the force of a spring, and so weigh the body, now we balance the centrifugal force against the attraction of the two

stars, and so weigh the stars. In general, it is only when a star is attracting something else that we can measure the force of attraction, so that measurements of star masses are practically confined to binary stars. It turns out that in contrast to the brightnesses and sizes of stars, both of which show a range of several million times, stars do not vary much in mass. A mass of 100 times the sun is about the known upper limit, while the lower limit is about one-tenth of the sun's mass. We shall return to the subject of star masses presently. Now we must consider a special sort of binary star where we can measure star radii directly.

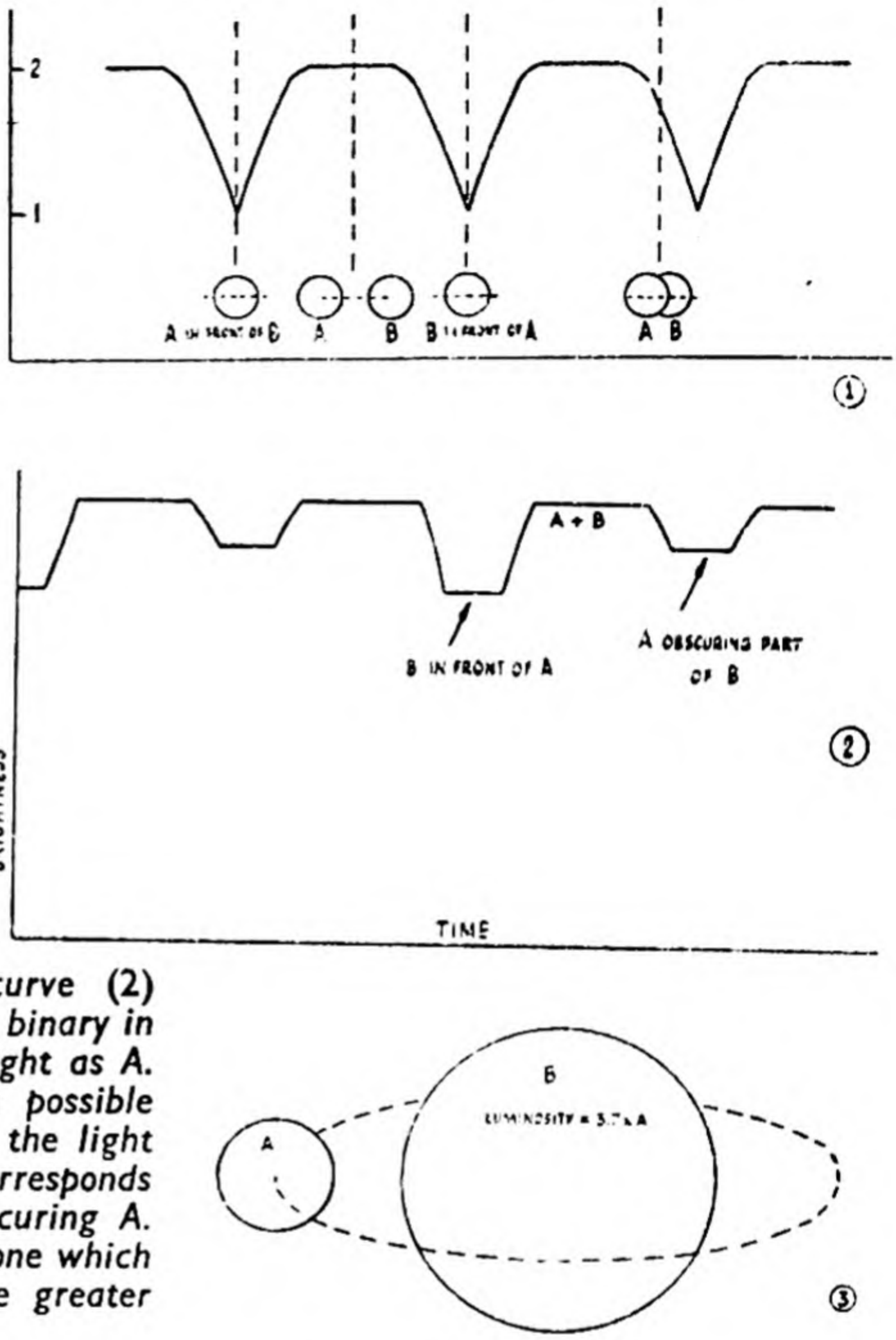
In Chapter III we made a table-top model of the solar system. We can make a similar model of a binary star. We put two stars on the table top and make them move round each other in orbits, so that they always stay on the table top and never move up or down. In this model the table top defines what we call the *orbital plane* of the binary. Now walk round this model and look at it, but don't restrict yourself to the case of standing on the floor. Stand on a chair and look down at the model—you will then see the two stars circling round one another. Take a three-quarter view and you will see them moving in oval paths. Squat down and squint along the surface of the table, and you will see the two stars shuttling backwards and forwards, and passing in front of each other twice in every circuit.

Now the orbital planes of binary stars are tipped in all directions in space. Some appear to us full face: some three-quarter face, and some edge on. We cannot alter this state of affairs: we are tied to one position in space and cannot climb about and look at the stars as we would like: we must take them as they come.

A few binaries are seen in the edge-on position and then twice in every circuit they get in each other's light, or eclipse one another. In each circuit of such an eclipsing binary there are two eclipses, one when A gets in front of B, and one when B gets in front of A. In such a case, if the dimensions of the orbits can be found, the radii as well as the masses of the two stars can be determined.

When the two stars are separated the light from both is seen: when one begins to eclipse the other the light from the

Fig. 21. *ECLIPSING BINARY STARS*



A binary system is a pair of stars moving in orbits about one another under their mutual attraction. If the orbit is seen edge on, the stars pass in front of one another, producing an eclipse. The observer cannot see the two stars separately: all he sees is a single star whose brightness varies regularly. (1) shows the graph of light variation or 'light curve' of two stars of equal size and brightness passing exactly in front of one another. The argument can be reversed: the brightnesses of the stars, their diameters and distance apart can be deduced from the light curve. For instance, the light curve (2) would be produced by the binary in (3): B is 3·7 times as bright as A. An alternative solution is possible since we cannot tell from the light curve alone which trough corresponds to B, the larger star, obscuring A. The solution chosen is the one which gives the smaller star the greater brightness per unit area.

pair is suddenly reduced. After some time the stars are clear of one another once more and the original brightness is restored. In most cases all that is seen is a star whose brightness varies in the manner indicated in Fig. 21. The general analysis is difficult, but it is possible to see how the radii are determined by taking an especially simple case in which the stars are exactly alike in brightness and radius and pass directly in front of one another. When the stars are in line the light from only one will reach us and it will be half of the light received when there is no eclipse, and the two eclipses, A in front of B, and B in front of A will be exactly the same.

These ideal conditions never hold in practice, so let us take

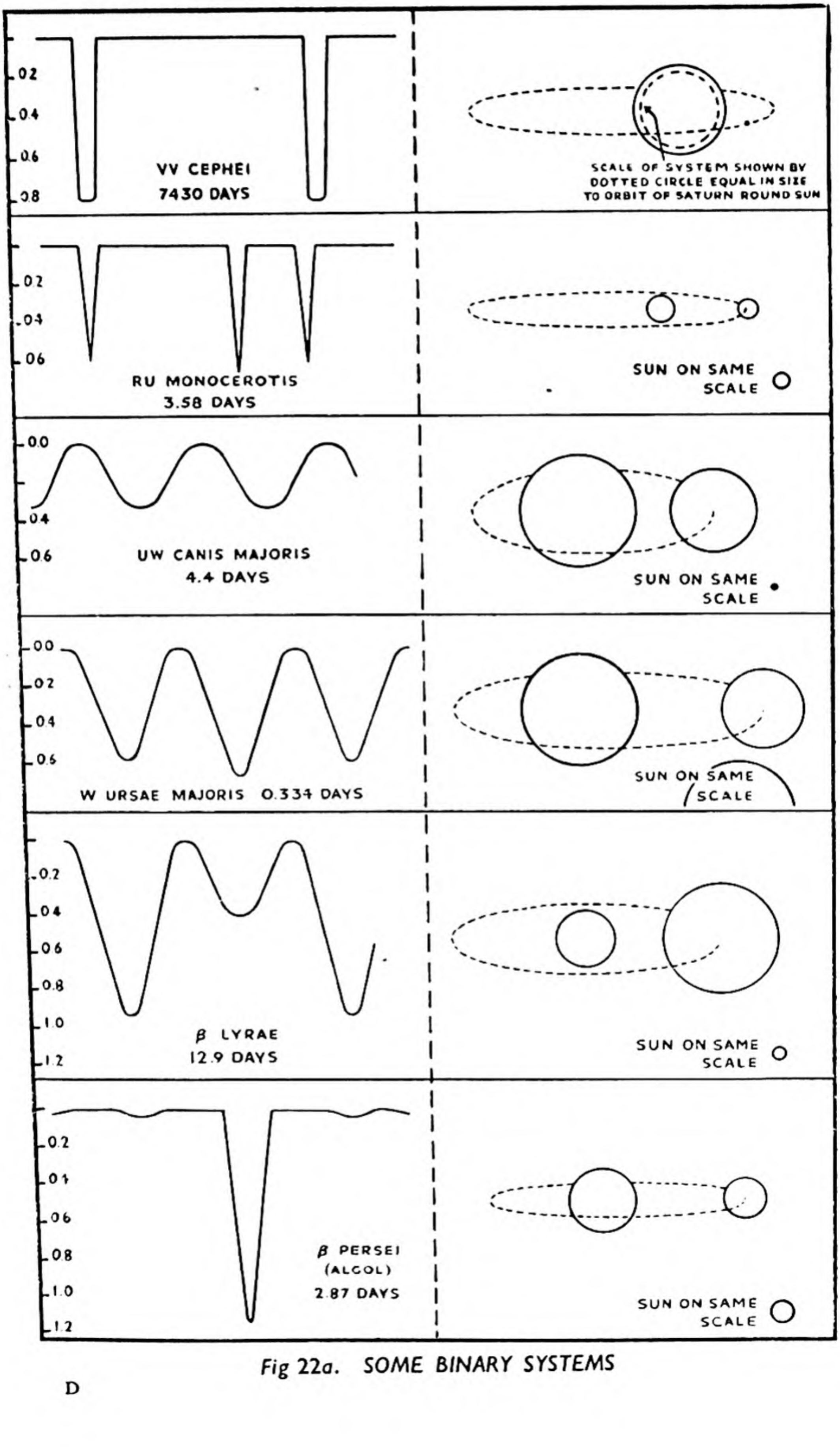
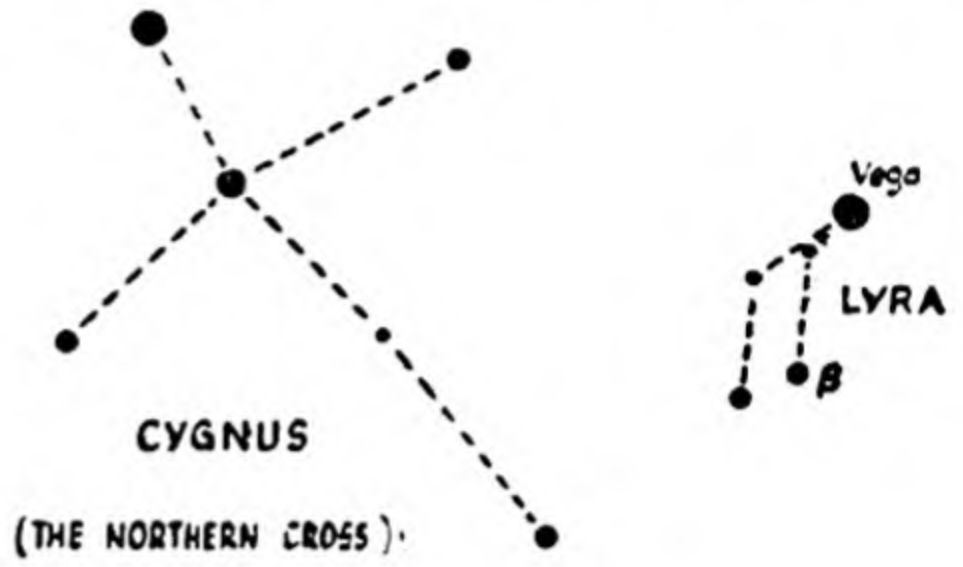


Fig 22a. SOME BINARY SYSTEMS

Fig. 22c. RECOGNITION CHART FOR ALGOL

Fig. 22b. RECOGNITION CHART FOR β LYRAE



a more complicated case in which A is a large star with ten times the radius of B, i.e. 100 times the area, but A and B still pass directly in front of each other. When A is in front of B, B is invisible, and the reduction in light is that normally received from B. Thus gives us B's brightness. When B is in front of A we get B's light plus 99 per cent of A's, and the reduction in light is 1 per cent of A's. In practice the argument goes in the opposite direction. It is possible to determine how many per cent of A's light is lost when B is in front, that is we can get the ratio of the radii of the two stars. There are of course complications, a particular one being that the big stars are not necessarily the brightest, but mathematical methods are available for analysing eclipsing binary star systems and in many cases the masses and radii can be found. Some known systems are illustrated in Fig. 22a.

These examples illustrate the fact that the astronomer must get what information he can, often by roundabout routes, but one of more important ways of studying stars is to make one, in imagination if not in fact, and compare its behaviour with real stars.

The important thing about the stars is that they appear to be fairly permanent, so that if we start out to make a blue-print for a star we must arrange that it will not suddenly collapse or blow up. The easiest way of doing this is to arrange that all the matter inside the star is quite still. Later on we may have reason to modify this idea in the extreme outer skin of the stars, but on the whole we believe that we are correct in thinking that all the gas inside the star is stationary and is not flowing about in streams. In a building built of bricks each brick is supported by those underneath, and in turn supports those on top. The bricks out of which a star is built are lumps of gas, and there is no mortar between to separate one from another, but all the same, if, in imagination, we divide the gaseous material up into small parts, the same rule must hold as in the case of the solid bricks of a wall—each is supported from underneath, and, in its turn, supports what is above.

The support of these gaseous bricks is of two kinds—first there is the pressure of the gas below, and secondly there is the pressure of radiation. This second factor is one which we have not mentioned before because it is one which does not come into our ordinary experience. Radiation does exert a pressure when it falls on matter, but at low temperatures it is too small to be detectable. Theory shows that this pressure increases with the fourth power of the absolute temperature: it becomes appreciable at about 50,000 degrees when the radiation pressure is about one pound per square inch. However, the way in which this varies with temperature means that if we double the temperature we multiply the pressure by sixteen times. At a million degrees, therefore, the radiation pressure is up to 160,000 pounds per square, or about 80 tons, and at a temperature of about 40 million degrees, such as we believe is attained at the centres of the stars, radiation pressure accounts for about 200 million tons per square inch. That is to say, the radiation alone coming out from the centre of a star could support, on each square inch a force of about 200 million tons, and this is sufficient for radiation pressure to play quite a detectable part in the economy of the star.

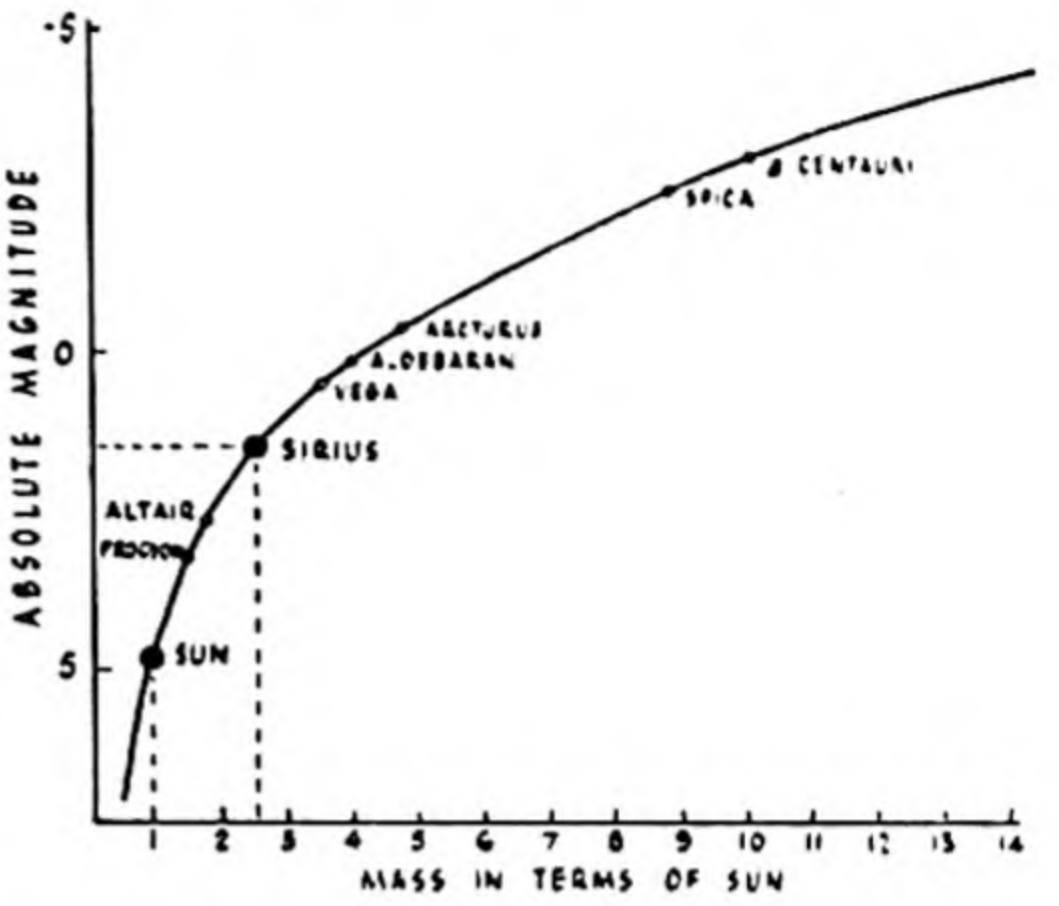
If we think of our star as a sort of balloon, the forces which —if they were not counterbalanced—would blow it up, are,

therefore, the pressure of the gas composing the star, and the tremendous outflow of radiation from the interior. The counterbalancing force is the attraction of the whole star for the gases of which it is composed. These two must just balance. If, for example, the pressure from the inside were too great, the star would swell up, the gas inside would have more room, the pressure would fall, and the star might settle down to a new state in which it was a good deal bigger than before. On the other hand, if the gas and radiation pressure were not as great as the gravitional attraction the star would shrink, and might settle down as a much smaller star then before.

So, if a star is a permanent unchanging thing, the radiation and gas pressures must just balance gravity all through it. We can if we like think of it as floating so much gas on a given supply of radiation. If there is too much gas, the gravitational attraction will be too great, and the star will change, probably increasing its brightness until a balance is secured. This rough idea that you can float just so much matter on a given supply of radiation is confirmed by detailed calculations. There is in fact a relationship, predicted theoretically by Sir Arthur Eddington, between the brightness of a star and its mass. The confirmation rests of course on observations of brightness of stars whose masses can be determined, namely the components of binary stars, and it is both a confirmation of the theory and some assurance that these binary stars are not peculiar in other ways, that we find that the mass luminosity law is obeyed. We have, therefore, a means of weighing these stars (Fig. 23).

This discussion of conditions inside stars has other consequences. It appears that the temperatures are so high that the atoms will be in a very damaged state. Life for them is so fast and furious, they collide with other atoms so often and move so rapidly, that each atom has lost almost all its normal quota of attendant electrons. Matter in this broken up state is a good deal simpler than the matter we commonly meet, and a good many of the differences between the diverse chemical elements which we know are rubbed out. The principal difference which remains is that hydrogen behaves differently from all the other elements, and this is a most

Fig. 23. *THE MASS LUMINOSITY LAW*



There is a relation between the absolute magnitudes of stars and their masses. This law is based on cases, namely binary stars, where the masses can be found. The masses of various familiar stars as deduced from this curve are shown. In some cases these may not be exact, since it is unlikely that all stars are built on exactly the same pattern. The law must be regarded as a general guide to masses. Sirius A with a mass 2½ times that of the sun, and 3½ magnitudes brighter, lies exactly on the curve. The range of absolute brightness shown in the diagram is about 100,000 to one (12½ magnitudes); the range of mass is only about 30 to one. This is generally true; star masses have a smaller range of variation than almost any characteristic of stars.

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important fact, for a variation in the proportion of hydrogen in a star has a considerable effect on its general constitution. It is in fact possible to argue backwards from the stars which we can see, and to deduce how much hydrogen they contain. We cannot do the kind of detailed chemical analysis of the centre of a star which the spectroscope enables us to do for the visible outside layers. It must be emphasized that we are dealing with the most inaccessible regions in the universe—regions which are buried under perhaps millions of kilometres of the hottest gases of which we have any experience. Even so, we can make a rough estimate of how much hydrogen there is. There is in fact a lot. The centres of the stars appear to be about 40 per cent hydrogen by weight.

In numbers of atoms this is even higher. It means that there must be something like twenty times as many hydrogen atoms as there are atoms of all other kinds. The great variety of star spectra is due mainly to differences in temperature and mass. Here also is the clue to the solution of a very important problem—how do the stars manage to generate their supplies of radiation which they pour out unchecked apparently for millennium after millennium?

If we take the case of the sun and add up all its present heat energy we find that this comes to enough to supply the

sun's heat and light for 47 million years at its present output. Arguing backwards in time it is found that if the sun contracted from an infinite dispersion and used the heat generated by the increasing pressure inside, then it could have been radiating at its present rate for only ten or twenty million years. But it is known that the rocks of the earth's crust are about 1,300 million years old, so that, unless the earth is older than the sun, the sun must have some other source of energy to draw on.

Clearly the sun must have some far more prolific supply of energy and the first hints as to what this might be came when it was discovered that experiments in which the actual central nuclei of atoms were disrupted could produce large supplies of energy. This possibility has become familiar with the production of the atomic bomb which uses a special property possessed by the nuclei of certain heavy atoms. In the classical 'atom-smashing' experiments on light atoms it was impossible to get out more energy than was put in. The atoms were disrupted by bombarding them with fast-moving nuclei of other atoms—those of helium, hydrogen or heavy hydrogen and most of them just went straight through the gaps between the atoms or between the nuclei and surrounding electrons. Perhaps once in a million times there was a direct hit on a nucleus and much more energy was given out than had been given to the bombarding nucleus to make it move fast enough to be deadly. There was a gain of energy in the successful cases, but the process was successful only once in several million times.

What was needed in this type of experiment to make transmutation go on at a reasonable rate was to subject the material to a continuous shower of very fast particles and to have so much of it, that every particle would eventually strike and cause a transmutation. This can only happen in some place where particles are habitually moving as fast as they do in atom-smashing experiments. The only place we know of is the centre of a star, where the atoms of which the gas is composed are moving about at the necessary high speeds, continually colliding, and presumably causing transmutations. Transmutation of the elements is one of the commonest processes in the universe and it proceeds in its most inaccessible parts. The energy liberated in the transmutation flows out through the stars and keeps them in being.

So far on general grounds; to understand the details is more difficult. It was clear that if hydrogen was so common, then hydrogen must be the fuel which kept the stars going, and the energy-giving process must be the conversion of hydrogen into something else. It cannot be the breaking down of hydrogen into anything simpler, because hydrogen is the simplest atom of all. It must be the building-up of hydrogen into something more complex. Various considerations suggested that it must be the building up of hydrogen into helium.

Now a helium atom weighs a little less than four times a hydrogen atom and it was known that if four hydrogen atoms could be persuaded to amalgamate into a helium atom, energy would be emitted. However, the probability of this happening directly is very small, and the process would go on far too slowly to produce the required amount of energy. Some roundabout route must be discovered. The idea was that the building-up process must go on in several stages: that some other atom must amalgamate with a hydrogen atom: that this in turn must pick up a second one and so on, and that in the end, the result of picking up four hydrogen atoms one after another must be a more complex atom which would split apart, giving a helium atom and the original 'carrier' atom. Several scientists attempted to put together the atomic processes observed in the laboratory in a string so that this could be achieved, but they ran into difficulties.

Some of them had to assume the existence of processes which had not been observed in the laboratory. Others concocted processes which unfortunately went backwards as fast as they went forwards, so that there was no output of energy at all. In the end Bethe and Gamow in 1938 worked out a process in which the hydrogen atoms were tacked successively on to a carbon atom and which involved only atomic changes which had been observed in the laboratory. What is more the process went on at a steady rate and gave out the right amount of energy, but not all in one burst or in a mere trickle.

The problem of the energy generation of the stars is therefore solved as far as we know. Stars shine because they are converting their hydrogen stock into helium by an indirect process in which the hydrogen atoms get caught up and

amalgamated with carbon atoms, each of which takes up four hydrogen atoms in succession (emitting energy during the process) and the final result splits apart to give a helium atom and a carbon atom.

Presumably the hydrogen content of the stars is steadily decreasing and the helium content increasing, but the process is too slow to be detected in a lifetime. The sun, for example is believed to have enough hydrogen to keep it going for 4,000 million years, unless something should happen to it before all its hydrogen is converted.

Thus we now know enough about stars to be able to give a recipe for making one. Take a mass of hydrogen from 100,000 to about ten million times the mass of the earth according to the quantity required. Add metals to taste, mix in a little helium, and season with carbon and nitrogen. The thing will probably get hot on its own account, but if it does not blow up or collapse will settle down and become a perfectly good star with a diameter of anything from 100,000 to 100 million miles, and will emit radiation accordingly.

It is worthwhile adding a word on the highly speculative subject of the evolution of stars. All the stars must be losing mass, and, if they continue to obey the mass-luminosity law, consequently also becoming fainter. Their hydrogen content must be decreasing and their helium content increasing, which means that even if their size is not changing their density of matter must also be increasing.

It is unfortunately rather difficult to separate out in calculation the influence of the hydrogen and the helium content of stars, and this, together with the general uncertainty of the very difficult calculations, means that we cannot arrange the stars in order of their hydrogen content. If we could, then we might assume that the stars with a lot of hydrogen were young ones which would eventually change into those with less hydrogen. Various attempts have been made to plot the evolutionary sequence, usually assuming that the stars which we see represent different stages in the æon-long process of evolution. It is tempting to think of the stars as evolving along the occupied parts of the Russell diagram—giants getting smaller and hotter until a very high temperature is reached, followed by a steady slide down the dwarf branch

to extinction when all the hydrogen has gone. Indeed, such facts as the observed steady increase in the density of the stars as this track is followed support such an idea, but the matter is still quite unsettled. In particular we are left with the question: why have we stars of all types? Were they in any sense 'created' at different times and if so are there stars starting off their careers even now? Again, the very brightest stars are radiating far faster, even for their mass, than dwarfs and so are evolving far more quickly. They can therefore only have a limited history behind them which is far shorter than that which has elapsed for the stars which we are inclined to think are 'older' and nearer senescence and death.

Any answer is just a guess so far. We must leave the speculative heights and turn to the nearest and by far the best observed star, the sun.

Chapter Six

THE SUN

THE sun is the only star of which we have a thorough knowledge, We have already used a number of data connected with it, and they may be collected here for convenience:

Apparent magnitude: —26·7
Absolute magnitude: 4·85
Spectral type: dwarf G0
Diameter 864,000 miles = 109 × earth
Mass 332,000 × earth.
Mean density 1·4 × water
Effective temperature 5,830°K
Mean distance sun-earth 93,005,000 miles
Angular diameter 31′ 59″

The solar spectrum is unrivalled for its revelation of detail and a fairly accurate analysis of the chemical composition of its outer layers may be made. Fifty-eight elements are known to be present and the most abundant occur in the following relative proportions by numbers of atoms:

Non-Metals:	Hydrogen	300,000	Metals:	Magnesium	63
	Helium	1,000		Silicon	20
	Oxygen	1,000		Iron	16
	Nitrogen	40		Sodium	16
	Carbon	25		Potassium	6
				Calcium	5
				Aluminium	3
				Nickel	1

There is some uncertainty about the proportion of non-metals to metals but the relative proportions of metals (sometimes called the Russell mixture) given above is fairly certain. Helium the rare gas which has the second lightest atom, was first discovered in the sun in 1868 by Lockyer and only later identified on earth.

These are the elements in the outer layers of the sun. Throughout its mass there is a proportion of about 33 per cent of hydrogen by weight (about 15 atoms of hydrogen to each atom of any other kind), which, on the hypothesis that the solar energy is due to the conversion of hydrogen into helium would keep the sun going at its present rate for 40,000 million

years. In the conversion of hydrogen into helium there is a slight loss of mass, since four hydrogen atoms weigh a little more than one helium atom. It is a law of physics that if mass disappears energy must appear, the two having a constant rate of conversion. The rate of energy radiation from the sun means that it is losing mass at the rate of about 240 million tons per minute corresponding to the conversion of some 2×10^{40} hydrogen atoms into one quarter as many helium atoms in that time. These figures seem fantastic, but they only mean that the sun is losing rather less than one-thousand millionth of one per cent of its mass in a century.

The total amount of radiation received by the earth from the sun (outside the earth's atmosphere) is in scientific terminology 1·93 calories per square centimetre per minute. That means that the heat energy falling on one square centimetre per minute is enough to raise a gramme of water through 1·93° C. This does not sound very much (it is a rather smaller rate of heating than is experienced when sitting three or four feet directly in front of the average electric fire) but it is this heat and light which keeps the earth warm, warms our air, evaporates the sea-water, causes rain and weather generally and provides us with all our sources of energy. Sunlight and heat which fell in the past on forests and on shallow seas promoted the growth of the trees and small animal or vegetable life which to-day we find as coal and oil under the earth. We are utterly dependent on the sun for these forms of power, for the rainfall which gives us hydro-electric power, and for tree growth which gives us wood fuel. All these, now or in the past, have acted as energy traps, and we draw on their reserves. The only exception to this is tidal power which takes energy from the rotation of the earth on its axis. This figure of 1·93 calories also enables us to calculate that in full sunlight we might, by catching all the sunlight and heat from one square yard, evaporate five pounds of water to steam in one hour, equivalent to rather less than two horsepower. A steam engine would convert something like $\frac{1}{4}$ of a horsepower of this into mechanical energy. We are in fact not likely to see extensive use made of sun-power especially in this country, although experimental installations have been set up in the Arizona desert.

We have in our description of the stars made considerable use of ideas and data derived from the sun, but the quite special importance of the sun in astronomy arises from the fact that it presents a visible disc, on which from time to time we may see changes taking place.

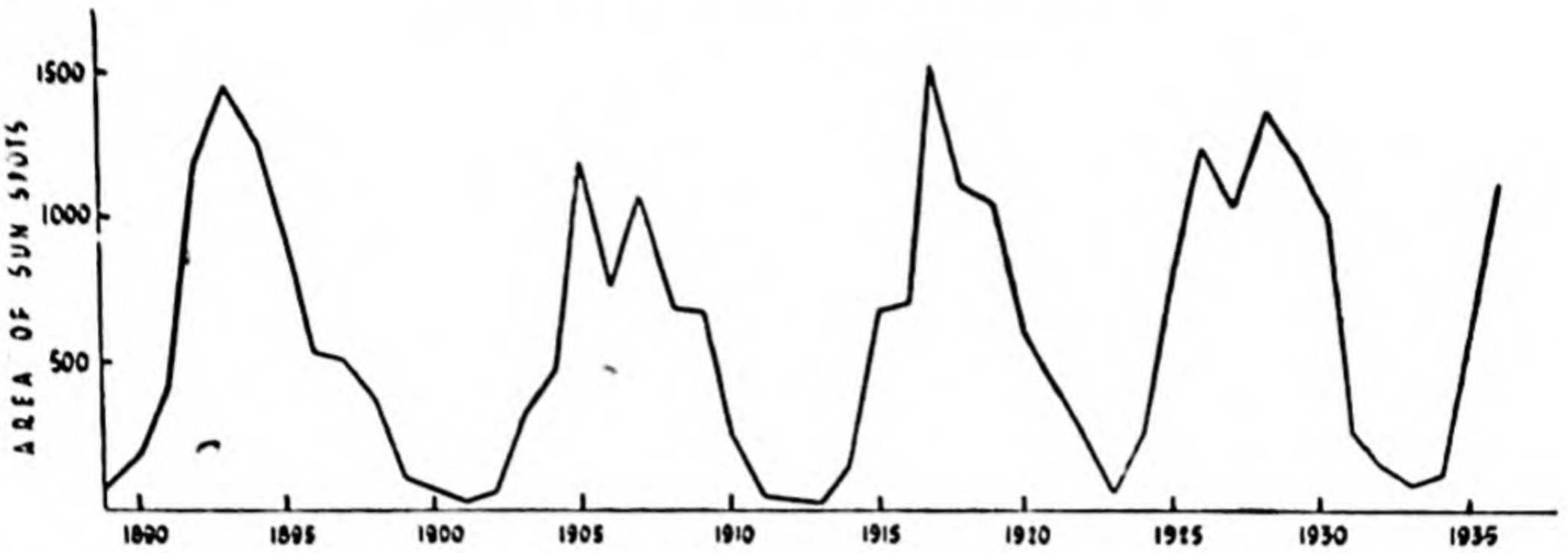
The most obvious of these is the appearance from time to time of sun-spots. These are areas of the sun's disc which are at a lower temperature than their surroundings and which appear dark by contrast: if the solar surface is screened off, the sun-spots can be seen to be intensely bright. The typical spot, which may be as much as several thousand kilometres across, consists of a dark central area or 'umbra' surrounded by a ring of intermediate brightness between the umbra and the solar surface. This is the penumbra.

A spot is really a three-dimensional phenomenon and the modern view is that they are regions where complicated movements of gas are taking place, not only up and down, but in a circulatory movement round the spot as well. These motions have been detected by the Doppler effect of the spectrum lines of the moving gases. Sun-spots are also the seat of intense magnetic fields which can be detected by certain effects which they produce on the sun-spot spectrum. There is a very definite tendency for spots to occur in pairs of opposite magnetic polarity, and not infrequently several pairs forming a large spot group occur together.

Sun-spots are impermanent and may disappear after a few days or weeks. During their life they are carried across the sun's disc as it rotates. We see the same point of the sun's equator at the centre of the solar disc at intervals of 27 days, so that if a spot group is very long-lived it may reappear several times at intervals of 27 days, undergoing changes of form and of position on the sun's surface during its life-time. These motions of the spots on, or rather in, the solar surface are comparatively small, but there are certain systematic features about them. For example, in a spot pair the following spot will tend to catch up and overtake the leader.

The spots give a fairly accurate indication of the solar rotation which, as in the case of Jupiter and Saturn, is not that of a solid body. The period of rotation at the equator is 24.7 days—since the earth is going round the sun, the sun

Fig. 24. THE SUN-SPOT CYCLE



The average area of the sun covered by spots in millionths of the visible disc is shown in the graph. There is a definite cycle of variation in about 11 years, but it is regular neither in size nor in the spacing of the peaks.

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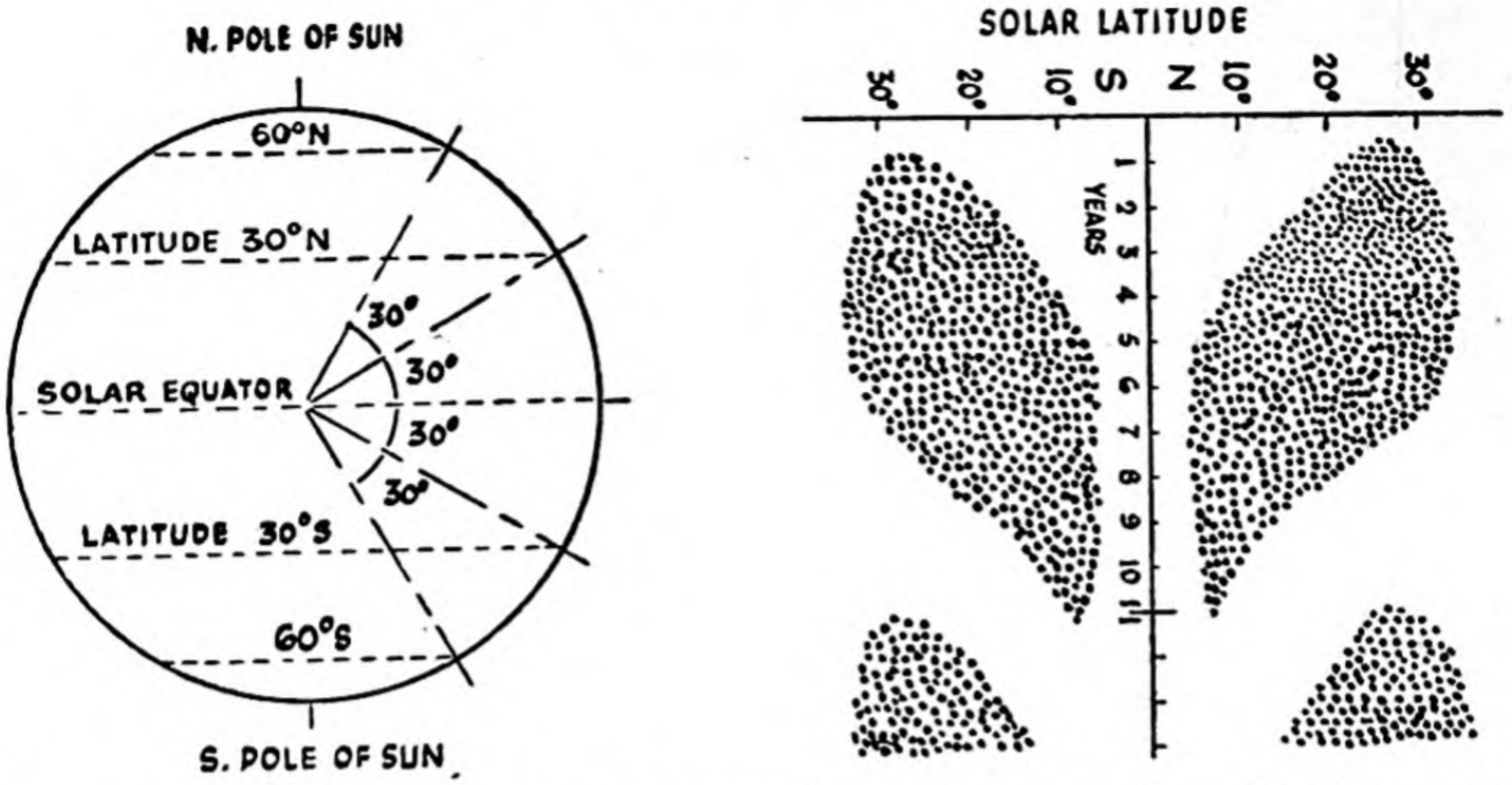
has to turn rather more than one revolution before the same part of its surface comes opposite the earth, which explains the 27-day interval mentioned above. The rotation period near the poles may be as much as 34 days. The figures derived from sun-spot movements are rather less accurate than measures of the velocity of the edges of the sun's disc, towards or away from the earth, which may be made using the Doppler effect.

The spottedness of the sun is not uniform, but varies fairly regularly in a period of just over eleven years (Fig. 24). This is the solar cycle, which begins with the appearance of a few small spots in comparatively high latitudes. As time wears on, more and more spots are seen, occurring nearer and nearer the equator until, about five and a half years after the beginning of the cycle, the spots are occurring with their maximum frequency. In the latter half of the cycle, spots become less and less frequent, and those which do appear are in lower and lower latitudes. At the end of the cycle a few spots of the old cycle are appearing near the equator at the same time as those of the new cycle are beginning to appear in high latitudes. If the latitudes of spots are plotted on a diagram they show a characteristic butterfly shape as shown in Fig. 25.

The sun-spot cycle is not perfectly regular: attempts at prediction for more than a little in advance have failed, but it is known that very many terrestrial phenomena, such as the occurrence of icebergs in the North Atlantic and the growth

Fig. 25. THE BUTTERFLY DIAGRAM



The sun rotates on its axis and it is convenient to fix the position of points on the sun's surface in terms of their latitude, or angular distance north or south of the solar equator, as indicated in the sectional figure of the sun (1). The first spots of a cycle occur in high latitudes, and then, on the average occur nearer and nearer the equator, the final spots of a cycle occurring about 10° from the equator just as the first spots of the new cycle are appearing. If the time and latitude of spots are plotted they give a diagram like the wings of a butterfly, of the kind indicated schematically in (2).

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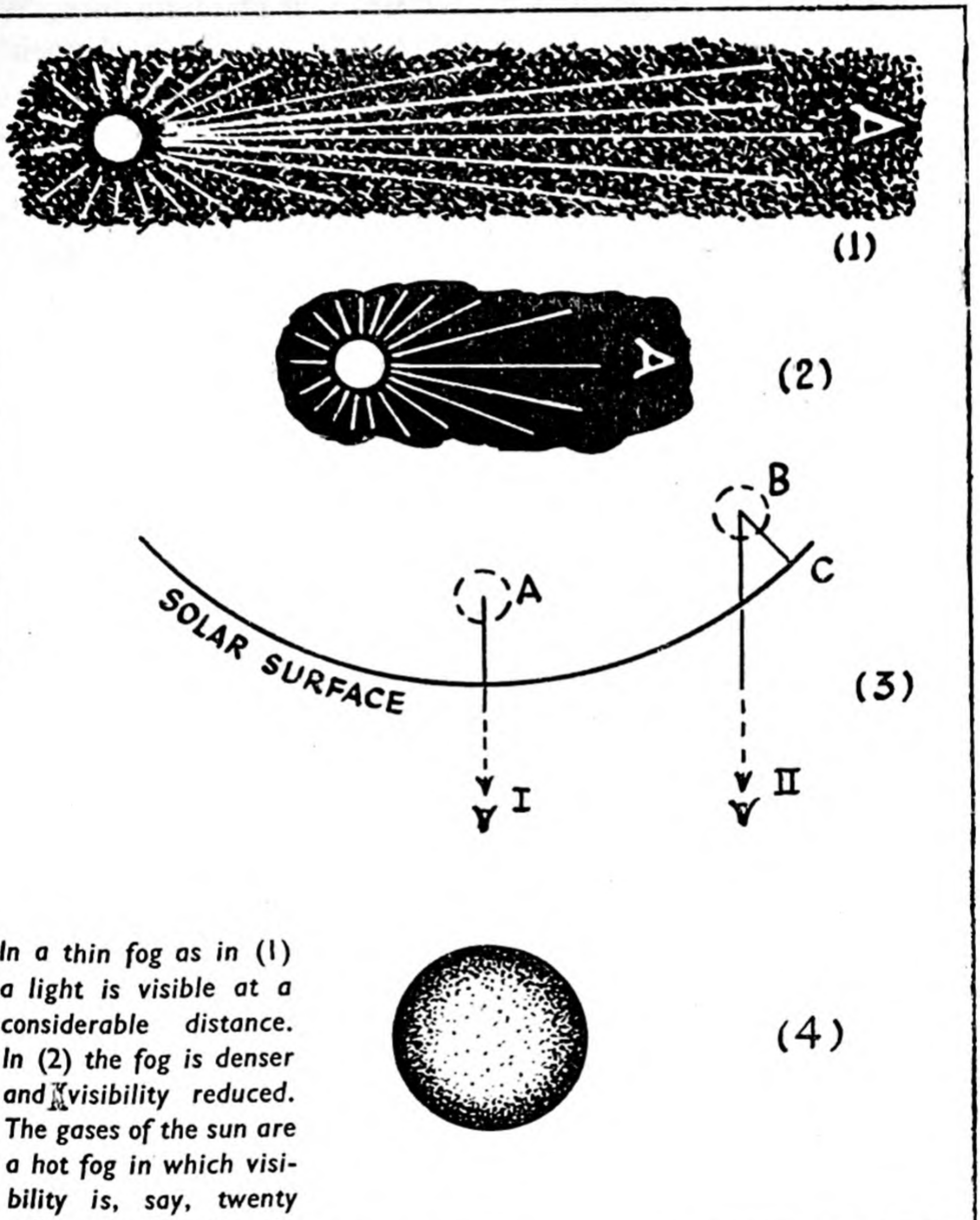
of tree-rings show definite rhythms in the same period of eleven years.

When the air is very clear, a definite fine mottling called granulation, which changes every few minutes, can be seen all over the solar surface. It is convenient to consider this along with a permanent feature of the sun's appearance, namely that it is very much darker at the edge or 'limb' of the disc than at the centre. The sun is a globe of very hot gas which is to a certain extent transparent, rather like a sort of hot fog. Now fogs are of different densities, and we might well describe a fog by the visibility in it—a fog with a visibility of ten yards would be called a ten-yard fog and so on. The sun's outer layers are probably something like a twenty-mile fog, so that if we look at the centre of the sun, then, as the diagram shows, we can see down into it for a distance of something like twenty miles. The gases of the sun get hotter and hotter with depth below the surface, so that at a depth of twenty miles the temperature may be something like, say, 10,000 degrees (we do not know what the exact figure is). On the other hand, when we look

Fig. 26. THE SUN IS DARKER AT THE EDGE THAN AT THE CENTRE



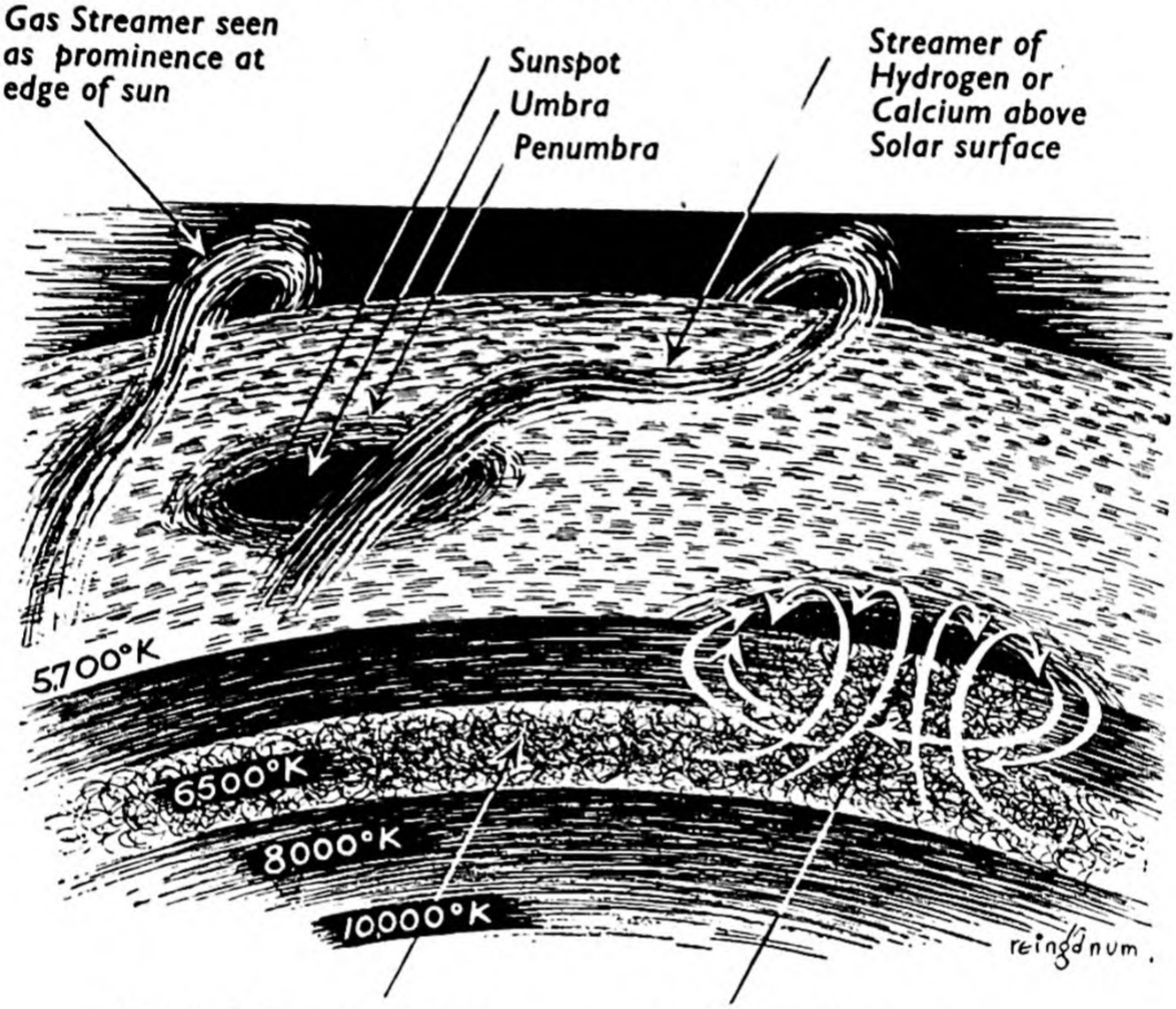
In a thin fog as in (1) a light is visible at a considerable distance. In (2) the fog is denser and visibility reduced. The gases of the sun are a hot fog in which visibility is, say, twenty miles. In (3) the observer at I is looking at the centre of the sun, and can see in to a region A twenty miles below the surface. The observer at II is looking at the edge or 'limb' of the disc, and can see twenty miles in to a region B. But B is only distant BC below the surface, so that the gases at B are cooler and less luminous than those at A. The edge of the sun therefore appears relatively dark as in (4). By studying the rate of darkening it is possible to infer the change of temperature below the surface in the outer layers of the sun.

at the edge of the sun, we are looking in at an angle to the surface, and our range of twenty miles is a glancing one. We see twenty miles in, but we no longer see to a depth of twenty miles. The light which we then see may be coming from a depth where the temperature is something like 7,000 degrees. But matter at 7,000 degrees radiates far less than matter at 10,000 degrees (only about one quarter as much) with the result that the edge of the sun looks darker than the middle (Fig. 26).

The temperature rises with depth, but there is evidence that it does not rise steadily. There seems to be reason to believe that there is a layer in which the gases are not lying quietly on top of one another, but moving up and down, and stirring about just as the milk in a saucepan of mixed coffee and milk rises up in little columns when the mixture is heated. These rising columns of gas are probably what we see as granulation. The columns come up from the hot depths and are hotter and brighter than their surroundings and produce the mottled granulation effect. Finally it may be that the spots are some more considerable kind of motion taking place in this region, and which for some reason leads to a general cooling of the gases, and in consequence, to the appearance of a relatively dark area (Fig. 27).

The fact that the sun presents a visible disc to the terrestrial observer has the important implication that it may be possible, by observing the variation of, for example, the surface brightness, across the disc, to interpret these observations in terms of the variation of conditions with depth in the solar atmosphere. The sun is the only star for which such observations can readily be made, and hence the only star about which we can have direct observational knowledge of the variation of conditions with depth, and much of modern solar research is concentrated on this type of problem in the hope of gaining this knowledge. There are considerable difficulties of interpretation in the observations. The only stellar case in which we might hope to gain information about the variation of brightness across the disc of a star is in the case of an eclipsing binary, when, during the progress of an eclipse, sections of the disc near its edge are all that remain visible. Here, however, there is the additional difficulty of disentangling variations

Fig. 27. THE SOLAR SURFACE



due to the darkening of the disc towards its edge from the reduction in the total light of the star as the eclipse proceeds.

We have referred briefly to sun-spots and cannot go further into a discussion of them. Extensive information about their magnetic properties, the circulation of the gases in them, their temperatures, and much more, can be found in such books as *The Sun*, by Abetti, or in general astronomical text-books. We must, however, include a word about special instruments which have been developed for the observation of the sun, and by means of which this information has been acquired.

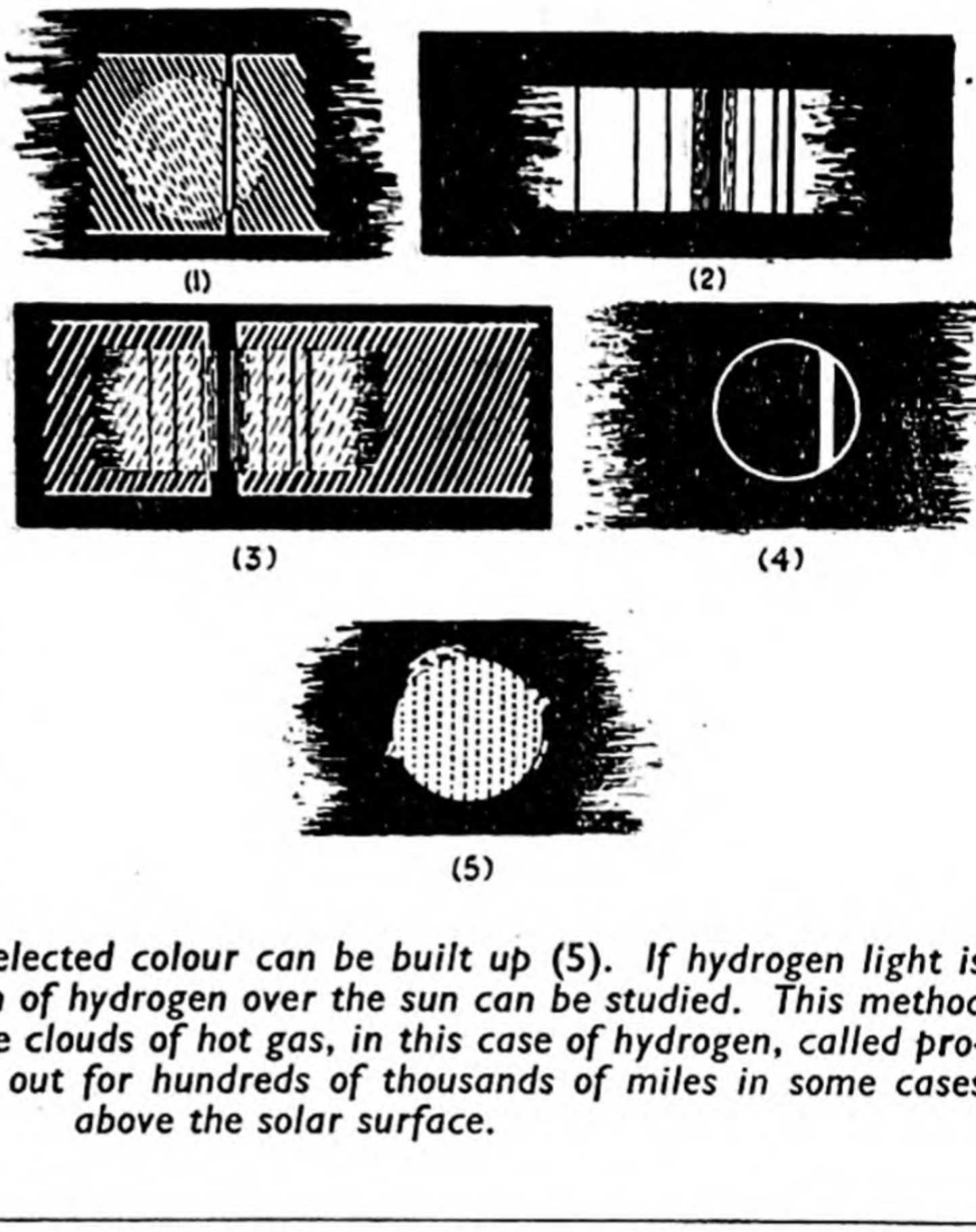
The conditions of solar observation are vastly different from those of stellar astronomy. A star gives far too little light to be comfortable, and our efforts must be concentrated

on catching as much of it as possible. Stellar telescopes therefore have large apertures and short foci. On the other hand the sun gives as much light as we can wish for. Quite a small aperture gives abundant light, so that the tendency is towards rather small apertures and long foci, giving high magnification, i.e. large images of the sun, and very little spherical aberration. Since the requirements are so different it is not surprising that special solar instruments have been constructed. A usual system is to have a very long telescope which is mounted vertically in a tower, the base being below ground, and the image from the telescope being fed into a spectroscope arranged in an underground chamber whose temperature can be kept accurately constant. If the temperature were to vary the dispersive power of the prisms would change, and the spectral lines obtained would be blurred.

Telescope and spectroscope are therefore fixed structures housed in these special enclosures. The light from the sun is fed into the telescope by an arrangement of two plane mirrors called a cœlostat. One of these turns on its axis and follows the apparent motion of the sun in the sky at such a speed that the reflected beam comes off in a constant direction. This reflected beam is then directed into the telescope. The arrangement can best be appreciated by a study of Plate I showing the solar telescope at the University Observatory at Oxford, which is probably the best example of this type of equipment in Britain. With such equipment good images of the sun about 7 inches across can be obtained and the solar spectrum from blue to red has an effective length of something like 100 feet.

The second type of instrument specially designed for solar observation is the spectrohelioscope or spectroheliograph designed by the American astronomer Hale (Fig. 28). Suppose we form an image of the sun by means of a telescope and let the light from one part of this image pass into the slit of a spectroscope. We shall then get a spectrum of the light coming from a narrow line on the sun, corresponding to the narrow line of light which is all that can get into the spectroscope. Now take a second slit and put it on the spectrum so that only the light from, say, one of the hydrogen lines passes through. Now we are seeing only a narrow strip of the sun illuminated

Fig. 28. THE SPECTROHELIOGRAPH



If the slit of a spectroscope is placed so as to admit light coming from a narrow strip of the sun (1) a spectrum of this strip is formed. (2). If a second slit is placed so as to let through only a narrow range of the spectrum (3) this strip of the sun is seen in light of only one colour. If this is the colour of a spectrum line of, say, hydrogen, the strip is seen only by the light of the hydrogen which is present (4). If the first slit is moved across the sun, but the second only admits light of the selected colour, an image of the whole sun in this selected colour can be built up (5). If hydrogen light is selected the distribution of hydrogen over the sun can be studied. This method also shows up flame like clouds of hot gas, in this case of hydrogen, called prominences, which stand out for hundreds of thousands of miles in some cases above the solar surface.

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only by the hydrogen light which it emits. If we move the first slit across the sun, and if we also keep the second slit over our hydrogen line, then we shall let through only the hydrogen light from successive strips of the sun's surface. If we catch these strips on a photographic plate we shall get a composite picture of the surface of the whole sun in *hydrogen light only*. This is the principle of the spectroheliograph. It enables us to get a picture of the sun built up in one colour or, what is perhaps more significant, in light coming from one chemical element only. It is not to be expected that the various elements in the sun's atmosphere are all perfectly mixed. It is probably not correct to think of them in distinct layers, but rather that the conditions at one layer are just suited to the excitation of, say, calcium, in another hydrogen and so on. Whatever the exact interpretation, it remains true that if we take a spectro-

heliogram in calcium light we get an entirely different picture from one taken in hydrogen light (Plate VI).

These spectroheliograms are most instructive but require a few minutes for the building up of the image. An alternative form of the instrument, the spectrohelioscope, is one in which only a comparatively small area of the sun is seen, but the image is seen by the eye as a direct picture of a small area of the solar surface, in light of one particular colour, often that of the red hydrogen line. This is achieved by the same system of two slits as before but the light which enters is made to come from different parts of the area of the sun under observation by putting a spinning square-sectioned rod of glass in front of the slits. This means that as the glass spins the light comes from different parts of a small area of the sun, and these strips are built up into a single small picture just as the transmitted spot of a television receiver scans its picture and by its rapidity of movement gives the impression of a whole area. The spectrohelioscope is ideally adapted for observation of the sun and particularly of those disturbed regions round sun-spots. The minute-to-minute changes can be seen taking place. Clouds of gas can be seen moving across the picture at very high speed and, by the use of the Doppler effect, it is possible to detect the movement of gases directly towards or away from the observer.

In a spectrohelioscope, using, for example, the hydrogen light, a cloud of bright hydrogen would show up as a bright mark. If this started to move upwards its spectrum line would be displaced slightly to the blue, that is, the light which it produced would be in a wavelength slightly-different from that to which the second slit was tuned. The marking would therefore disappear from the picture, but, if the second slit were shifted a little, it would reappear, the upward speed of the cloud being indicated by the wavelength shift of the second slit. In an actual spectrohelioscope there are two points of difference. Most markings are seen dark and not bright, but the same argument applies, and the shifting of the wavelength is accomplished, not by moving the second slit, but by turning a block of glass through which the rays pass, the effect of this being to shift the spectrum slightly. This line shifter is graduated directly in kilometres per second, and by its

aid the operator can determine the upward and downward velocities immediately. Thus an observer may see a dark marking near a sun-spot. This marking may in reality be a huge cloud of hydrogen, perhaps a thousand kilometres across, which is being thrown up with what, by terrestrial standards, is explosive speed. The operator turns his line shifter, and the marking disappears. It remains in his field of view at the mark 100 km. per second. Then suddenly it fades from view. A shift of the dial and it reappears, moving now perhaps at 150 km. per second. So it goes on; the observer plots out the speed at each moment, perhaps for ten minutes on end, and a later analysis of his observations may tell him that at the end of this time the cloud has reached a height of perhaps 60,000 kilometres above the sun's surface. By this time it may have changed shape or become dissipated and be lost to observation, but an hour or so later another marking may have appeared and its life history traced in turn. The sun's surface is always changing and is most disturbed near the time of sun-spot maximum.

These clouds or streaks of gas, often associated with sun-spots, are variously named. Those which appear bright in calcium light are called faculæ, while the dark streaks and patches in hydrogen light are flocculi. If these could be seen from the side they would appear as great arches of glowing gas towering for thousands of kilometres above the solar surface, and when such a streak runs out to the limb of the sun it is seen to be identical with the gas clouds, known as prominences, which are seen at the edge of the solar disc and which often have a fantastic beauty of form. The vertical movements, which can be measured by the Doppler effect when the prominences are seen against the background of the solar disc, can now be seen as actual motions of the gas. The spectrohelioscope shows up the prominences at the limb of the sun because all the extraneous light in the other regions of the spectrum which would otherwise obscure them is cut out. The most tantalizing thing about the whole business is, however, that if the gas clouds are in a position where their vertical and horizontal movements can be accurately measured, i.e. when we see them against the sun's disc, then we cannot see their form properly, although we can see the sun's surface

underneath them. On the other hand, at the edge of the sun's disc their form can be seen, but we cannot see the surface beneath them.

These are matters of great importance, for in recent years, the study of prominences, their relation to sun-spots, their origin and a host of other matters have aroused very great interest. The actual motions of prominences particularly has caught the attention of astronomers, for by various methods these can be followed in detail, and it has been found that, contrary to the obvious idea that prominences are a sort of 'flame' leaping out of the sun, their usual motion is the reverse, and they stream downwards at least as often as they go upwards. It must be emphasized that a flame is a region of chemical action, and the prominences are too hot for any chemical compound to remain in existence, i.e. there is no chemical action going on at all. The prominences streaming down give the appearance of heading for some definite point on the sun's surface: successive masses of luminous gas follow along what look like definite tracks, which end on the sun's surface. But, when we can see the prominence at the sun's edge, we cannot see what it is that distinguishes the end of the track.

This information has been derived as the result of new developments in solar research. One of these is a complicated engineering device of great ingenuity known as the spectro-heliokinematograph, which is installed at the McMath-Hulbert Observatory in Michigan (Plate I). It takes two or three spectro-heliograms every minute on ordinary 35 mm. cinema film, which, when projected, gives a speeded up motion picture of the prominence movements. This is undoubtedly a great achievement, but observations which are in some ways even more valuable have been made with another device so simple and so perfect that it has a tremendous appeal to the imagination. The reason why we cannot see the prominences in the ordinary way is that the full glare of the sunlight obscures them. When a total eclipse of the sun occurs, the moon passes in front of the sun, just cutting off the light from the disc, but allowing us to see the prominences standing up above the surface, not, as in the spectrohelioscope, in light of *one* colour, but in their full natural light.

Why should not one make one's own eclipse by putting up a disc of the right size and position so as to cut off the sun? A halfpenny about five feet away for example would give the right size. When this is done the direct sunlight is cut off, but the air is still full of scattered light which is so intense that the prominences are invisible. When the sunlight is cut off by the moon, the shutter is *outside* the atmosphere of the earth and there is nothing to scatter the sunlight round the edge of the obstacle. Clearly then, this experiment of making one's own eclipse must be done outside as much of the earth's atmosphere as possible. Bernard Lyot, the French astronomer who succeeded in doing this some ten years ago carried his heavy apparatus on his back to the summit of the 9,300-foot high Pic du Midi in the Pyrenees. The Observatory there is only accessible at all easily during the summer and the astronomers spend much of each winter marooned on their mountain top, with a large part of the earth's atmosphere and the dust and smoke of towns far below.

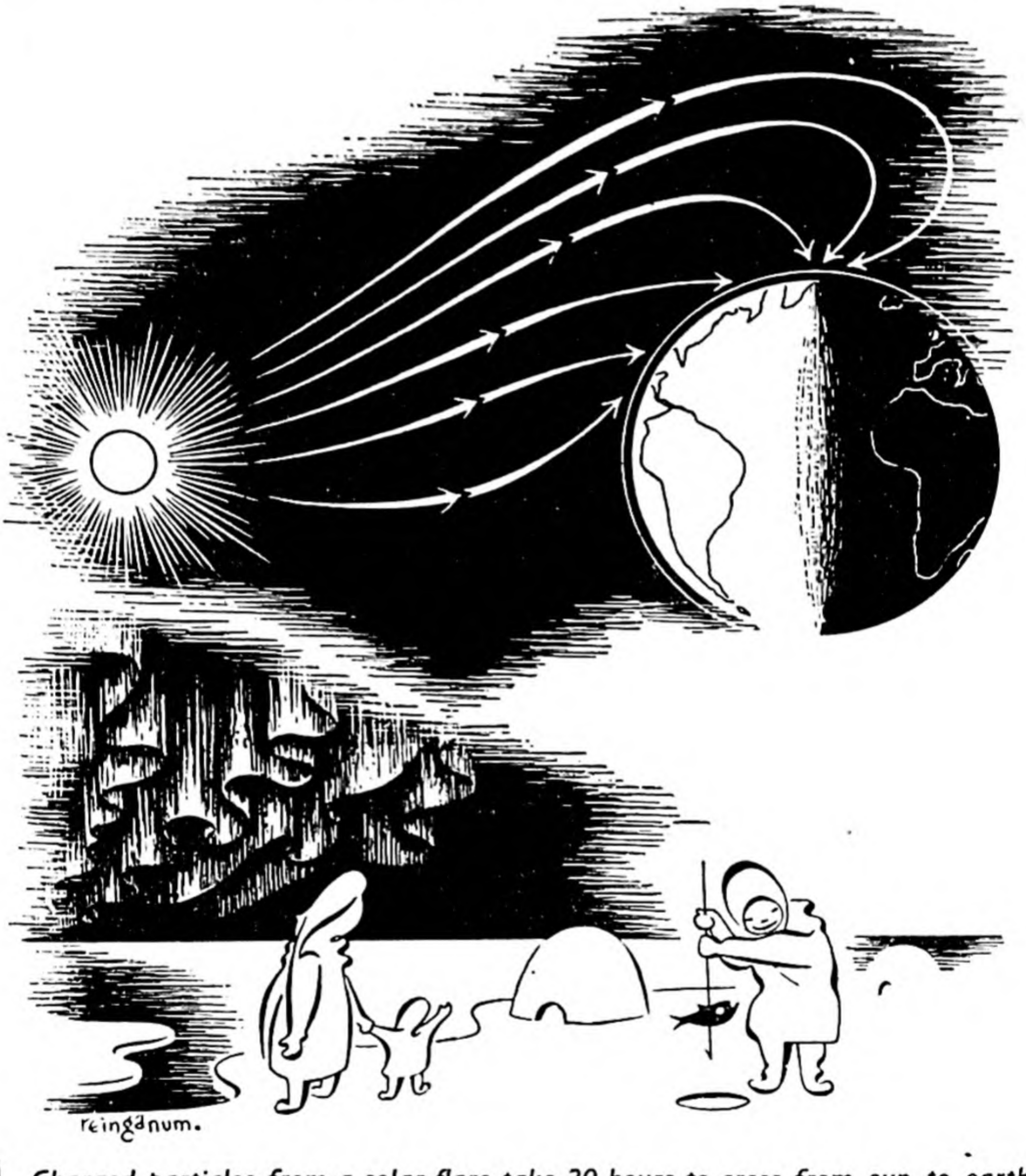
Lyot's enemy was scattered light. Even a scattering of far less than one per cent of the sunlight would defeat him. He eliminated one source of scattering by going up his mountain. Next he had to have a lens to form an image of the sun. If an ordinary lens is photographed it will be seen to be full of tiny bubbles, minute scratches on its surfaces, and blemishes of all kinds, each of which catches the light and scatters it. Lyot finally selected a lens which was as nearly perfect as possible. His telescope of special pattern—a coronograph—was constructed in the following way. The perfect lens was mounted in a long tube, blackened inside. It was not at the end of the tube but some way down, so that there was a sort of cylindrical cap in front of the lens which prevented light coming in at an angle from striking the lens. This lens formed an image of the sun on a disc which was just a little larger than the solar image. This disc was actually provided with an inclined mirror which threw the direct sunlight out to one side through a window in the tube so that it was kept completely clear of the apparatus. At this stage then, all that the telescope produced was an image of the sky round the sun, plus a certain amount of light scattered from the front lens. This had to be got rid of, so a lens was placed behind the disc,

adjusted so that it caught the scattered light from the *front lens* and threw it on to some absorbing screens. This left the image from the sky near the sun, and this was brought outside the tube by means of further lenses.

The apparatus worked just because of this scrupulous attention to detail. Before Lyot's time observations of the prominences in full light and of the faint pearly ring of light called the corona which is seen surrounding the sun during total eclipses, had been possible only for something like a hundred minutes—the total duration of all recent eclipses. Lyot could match this in a single day of observation. The corona must wait for its proper place in the story, but Lyot was the first man to see it at any time except during a total eclipse.

The McMath-Hulbert pictures of prominences in motion would be superb if judged alone, but they must take second place to the magnificent photographs of Lyot's. He too combined his observations into a motion picture, but his prominences show a miraculous wealth of detail, a wonderful feathery structure, a complexity of motion which is quite soberly beyond description. There are several copies of his film in this country. For the specialist it cannot be seen too often, while lay audiences are spell-bound at the spectacular beauty which is revealed. Glowing clouds float quietly above the sun's surface; suddenly a tongue of fire shoots sideways and down in a curved path. On its heels streams a thin wrack of cloud and yet another. Suddenly the sun's surface is convulsed, there is an explosive upheaval and a huge mass of gas is thrown clear of the sun's surface. These are the eruptive prominences. Another type consist of tall feathery columns of gas standing quite still and reaching up to heights of tens of thousands of kilometres. Their very immobility lends fascination to these strange events which proceed before our very eyes a hundred million miles away in space. Of all the strange and beautiful sights which the astronomer sees, these are probably the most fascinating. The definition of the McMath-Hulbert pictures is less good, but they provide information which Lyot's cannot, and are in a way supplementary to his. Lyot must cut out the sun itself to see the prominences. The McMath-Hulbert observers take in the

Fig. 29. SOLAR FLARES



Charged particles from a solar flare take 20 hours to cross from sun to earth. They are drawn in most abundantly near the magnetic poles and produce displays of aurora borealis and aurora australis.

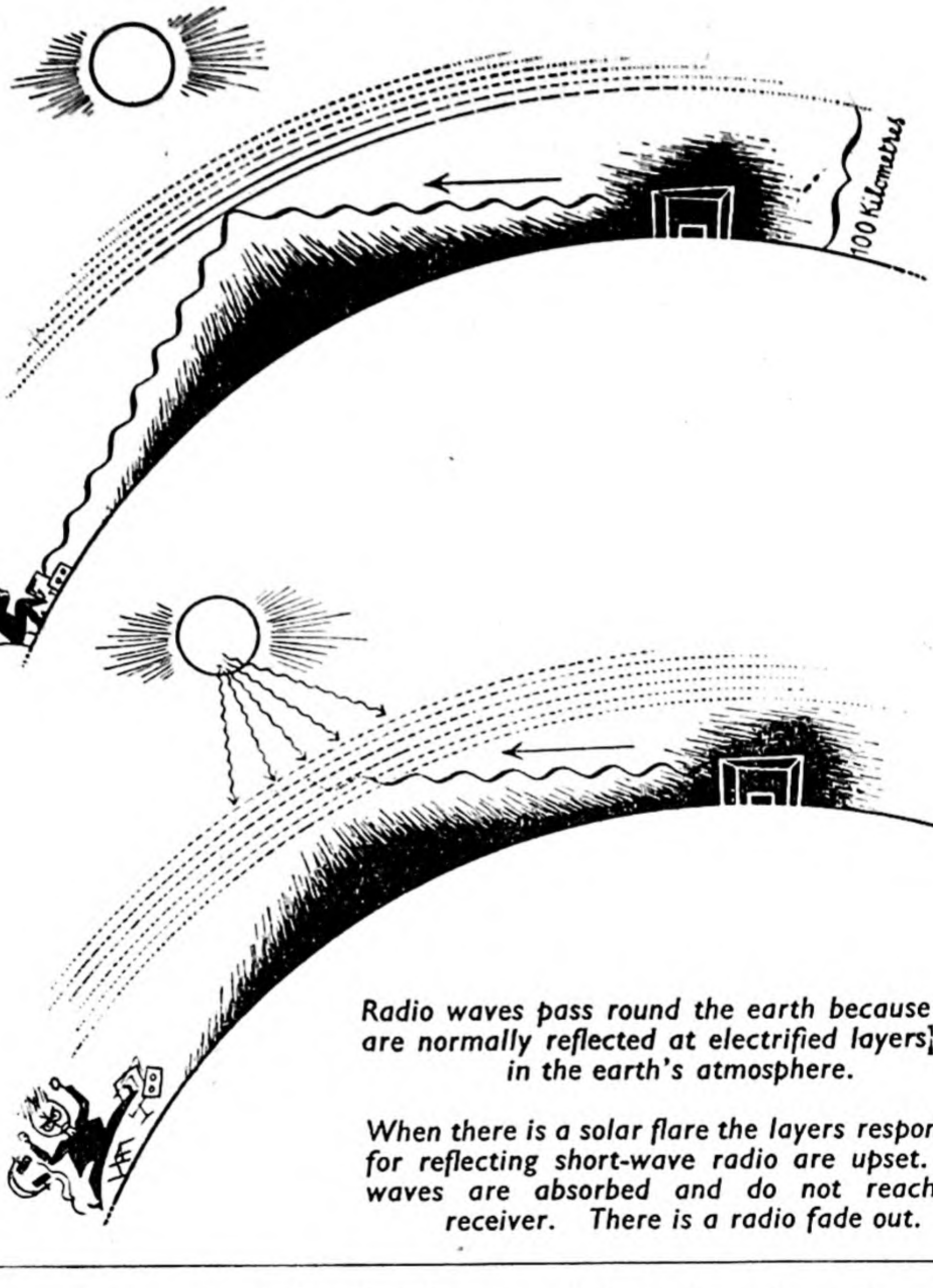
edge of the disc itself. The latter can show a type of prominence which the former cannot: these are the short spikes of gas which shoot upwards in a few minutes to heights of a few hundred kilometres and as quickly subside once more.

The astronomer who has seen these films could praise them endlessly for it is impossible for him not to be inspired with

glimpses of new problems and new possibilities of investigation. We must however turn to another fascinating aspect of solar research which deals with the phenomenon known as the solar flare and which occurs usually in these disturbed regions of the sun's surface where spots and prominences abound. The sequence of phenomena about to be related is not invariable. Often some elements are missing—why we do not know—but we will give the connected story as if it were always recapitulated in all its details.

From time to time solar observers notice, usually in one of these disturbed regions of the sun's surface, a brilliant patch of luminosity (Plate II). These luminous patches are short-lived and after about twenty minutes they disappear. In the spectroheliograph a dark marking may be observed above the patch which shows a rapid vertical motion, often initially upwards and later downwards. At the same moment as the bright patch or 'flare' is seen there is a slight interference with the earth's magnetic field. The magnetic traces which show the intensity and direction of the earth's magnetism at every moment show a small kick or crotchet. About twenty hours later, a time corresponding to that which might be taken by charged electric particles ejected from the region to pass from the sun to the earth, there may be a much more serious interference with the earth's magnetism, a phenomenon known as a magnetic storm. At the same time it may happen that a display of the aurora borealis may be seen. It is to be expected that these charged particles from the sun, some of which are drawn in by the earth's magnetic field will be moving very rapidly and will have a considerable effect on the atmosphere of the earth when they strike it. The kind of effect to be expected is rather similar to that shown when electrons are moving rapidly through a gas, as is the case in a so-called gas discharge tube. This is filled with gas at a low pressure and if a large difference of electric potential is applied between electrodes at the two ends of the tube, this will cause electrons in the tube to move rapidly through the gas, to interact with the atoms there and to cause them to emit light concentrated into their own special spectrum lines. This may be seen, for example, in neon advertising signs, where the red light is that of the red lines of the neon spectrum, or in the sodium dis-

Fig. 30. SOLAR FLARES



Radio waves pass round the earth because they are normally reflected at electrified layers high in the earth's atmosphere.

When there is a solar flare the layers responsible for reflecting short-wave radio are upset. The waves are absorbed and do not reach the receiver. There is a radio fade out.

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charge lamps used for lighting arterial roads, where the light is that of the yellow lines of sodium.

Owing to the very low pressures of the atmospheric gases at the heights of sixty miles or more at which the auroræ are observed, the spectra are very different from those produced by the same elements under more familiar conditions. For many years, the green auroral line, which plays a not unimportant part in producing the colour of our night sky

could not be identified, but it was eventually proved that it was due to the familiar element nitrogen. It is not certain that these brilliant displays of red or green curtains of light which occur in the neighbourhood of the north and south magnetic poles of the earth are always due to some solar influence, but it is certain that the particles emitted as part of the phenomenon of the solar flare, and which are drawn in most copiously by the attraction of the magnetic poles of the earth, can cause very wonderful and intense auroral displays.

The final manifestation associated with solar flares concerns the transmission of radio waves. It rarely occurs to people that it is a very remarkable thing that it is possible to transmit radio waves from England to the Antipodes. It is as remarkable as being able to see round corners, for, in general, waves are propagated in straight lines. To see round a corner needs a mirror to reflect light waves. To transmit radio waves round a curved earth will be possible only if there is some agency to reflect the waves and prevent them going straight out into empty space. This agency is a reflecting layer, or rather a series of reflecting layers high up in the earth's atmosphere. They are electrical in nature and their degree of electrification or ionization seems to depend on the action of sunlight possibly because the atmosphere absorbs all the short-wave (ultra-violet) light from the sun. It is known that the degree of ionization varies in intensity with the variation in the sun-spot cycle, being greatest when the sun's surface is most disturbed, i.e. at sun-spot maximum. The frequencies used in short-wave radio transmission have to be varied according to whether the path of the rays is on the daylight side of the earth or on the dark side, and the optimum frequencies vary also with the sun-spot cycle. The detailed mechanics of the process are still under investigation, but it is now certain that the reflecting layers can be seriously upset by the presumably large increase in the ultra-violet radiation emitted by the sun during a solar flare. There is a very close correspondence between the occurrence of solar flares and fade-outs on the short-wave radio which occur simultaneously with the visible appearance of many flares. These are matters still under investigation and important research on these problems is being undertaken by Mr. H. W. Newton of Greenwich Observatory in collabora-

tion with Cable and Wireless Ltd., and the Post Office Research Station. In recent years there have been several very large solar flares, with magnetic storms, radio fade-outs and auroræ associated with them. Two of the biggest occurred in March and September 1941, the latter interrupting short-wave radio communication between this country and the U.S.A. and U.S.S.R. for several days.

The solar flares bring one right to the frontiers of astronomical knowledge. The explanation of their occurrence, and even more puzzling, of their non-occurrence on some occasions when conditions have seemed exactly right, must lie in the structure of the solar atmosphere, and we are not likely to make progress until we know a good deal more than we do about the outer layers of the sun. This is a particularly striking example of the way distinct sciences link up together and form a single unity.

The last solar topic on which we shall touch concerns the tenuous pearly white cloud which can be seen surrounding the sun during total eclipses, and which is known as the solar corona. Until Lyot made it possible to observe, at any rate the inner corona, without an eclipse, information about its constitution and structure had been gleaned during less than two hours of observation spread over half a century. The structure of the corona is almost completely mysterious. It is white in colour and its total light is only about one millionth of that of the sun. It becomes fainter as the distance from the sun increases and is detectable out to distances of a million miles from the sun's surface. Its shape and structure change with the sun-spot cycle. At sun-spot maximum it is very nearly circular in appearance, i.e. it must be an almost spherical cloud of gas; on the other hand, at sun-spot minimum it exhibits a series of fine streamers which run out along curved lines from the magnetic poles of the sun. It has a spectrum, many of whose lines were completely unidentified until recently. It is clearly at a very high temperature indeed, its energy in some respects being compatible with a temperature of 350,000 degrees. Here indeed is a mystery. How can these atoms support themselves so far from the sun's surface? Why is it that the whole cloud does not collapse? How is it, that its temperature can be so much higher than that of the sun itself,

when, throughout astrophysics we are accustomed to a state of affairs where the hotter layers are nearer the centres of the stars?

Two pieces of recent research have added more information but as yet, not more enlightenment. In 1936 there was a total eclipse of the sun whose belt of totality passed across the Soviet Union for a distance of 7,200 kilometres. No less than twelve eclipse expeditions were stationed along this line and saw the eclipse at different times. As the shadow of the moon swept over each station the observers experienced the eclipse and photographed the corona. The difference in time between the eclipses at opposite ends of this 7,200 km. track was 2 hours, which meant that when all the observations were put together the result was, in effect, a continuous observation of the corona for that time. The interesting thing about the results was that the various arches and streamers of the corona could be shown to originate in definite disturbed regions of the solar surface. It looks in fact as if the corona were continually being replenished from areas of disturbance on the sun itself, but exactly how we do not know.

The other investigation, rumours of which greatly exercised the minds of astronomers during the war, has been the identification of the unknown coronal lines by the Swede Edlén, who was awarded the Gold Medal of the Royal Astronomical Society in 1945. His discoveries have tantalizingly only produced new problems for solution. We have spoken already of the phenomenon of ionization. This means the loss of an electron from an atom, and it will occur at high temperatures. The residue of the atom—the ion—has a different spectrum from that of the original element, but for most elements this is well-known. Loss of a single electron is called single ionization, but in the case of an atom with many electrons in its normal state, multiple ionization is possible until all have been stripped away. The spectra of atoms even in a fairly highly ionized state are known in many cases. However, Edlén has finally identified the unknown coronal lines as due to the atoms of iron, nickel, calcium and argon, none of them less than nine times ionized and with some of the nickel atoms 15 times ionised. They were not recognized before because they are completely unfamiliar without their accustomed clothing of electrons.

Such a degree of denudation is most unexpected, for to produce this degree of ionization requires a temperature of something like 350,000° K. Edlén's intuition in looking here for the unknown lines was a stroke of genius. The identification has been made, but now what? Again we come back to the questions: how does something so far from the sun get so hot? The proper place for temperatures of 350,000° K. in most theories is far below the surface of a star. It may look as if these atoms had no business to be where they are, and certainly no right at all to be in their present state, but it is not our business to quarrel with facts. In conclusion, mention must be made of the recent work of Lyot which, if possible, surpasses his earlier observations of prominences. During the occupation of France he put into use a new and ingenious filter which cut out all light except that coming from the corona. His first picture which is one of the historic photographs of science, is shown in Plate V. Since then he has made continual observations of the arches and jets of the corona and finds in contradiction to the Russian observations, that they bear little or no relation to the prominences and disturbed regions of the solar surface.

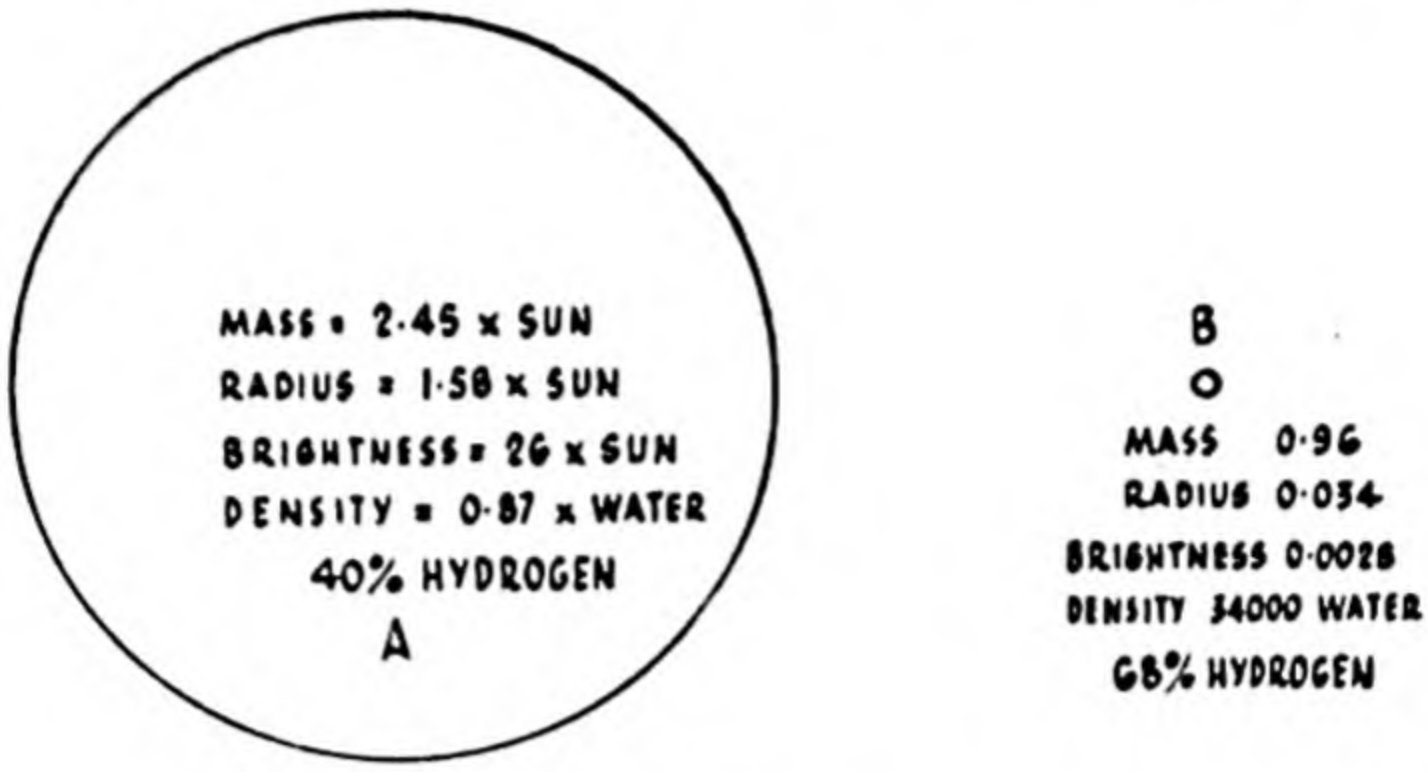
Chapter Seven

ODDITIES

THE scallywags and eccentrics of a family frequently have more charm than its staid and respectable pillars. So it is with stars: those out of the normal run present some of the most intriguing problems and have an importance and a usefulness out of all proportion to their numbers.

The first queer type of star which we shall discuss are the white dwarfs which are very hot (types A and F) but also very faint. Because of the high radiation output per unit area given by hot bodies, this must mean that these stars have a very small surface and radius. The first star of this type to be discovered was the Companion of Sirius. In 1862 Alvan Clark, while testing an 18-inch objective, noticed that Sirius, the brightest star in the sky, possessed a faint companion, thus confirming the observations of Bessel who had deduced from accurate measures of the position of Sirius that it must be moving round a faint companion. Sirius is a binary: and the masses can be found. The oddity of Sirius B, as the companion was called, only became apparent after the last war, when it was realized that the star was of magnitude 11·3, that its mass was 0·96 that of the sun and that it was *white*. This last fact enabled the radius to be calculated and it was found to be only 0·034 of the sun's radius. On this basis it could be calculated that the density of matter in Sirius B must be 34,000 times that of water, or over half a ton to the cubic inch. This conclusion was received with open doubt, but presently other stars of the same type were discovered, all being of planetary size and stellar mass, the smallest of all, van Maanen's star being about the same size as the earth. A direct test of these high calculated densities was provided by Einstein's theory of relativity, which predicted that, in an intense gravitational field, all spectrum lines should be shifted slightly to the red. Now the atoms in the surface of Sirius B must be in a gravitational field 800 times as intense as that of the earth i.e. a body

Fig. 31. THE TWO COMPONENTS OF SIRIUS



weighing a pound on the earth would weigh 800 lb. if placed near Sirius B. The prediction was confirmed by observation, for the red shift due to gravity could be separated from the red shift due to velocity, since Sirius A and Sirius B must necessarily be moving together through space. Since the gravitational force is proportional to the mass of the star divided by its radius, the red shift due to gravity provides another method of getting at masses and radii in the particular case of the white dwarfs.

There can be no escape from the conclusion that stars containing such dense matter do exist, and probably not uncommonly, for they are only bright enough to be visible when very close to us. Five such stars are known, four of them within five parsecs of the sun. The total star population within this distance is about forty, so that if these nearby stars are a fair sample of the general star population, white dwarfs must be among the commonest stars in the universe. This is an extreme example of the selective effect of brightness already mentioned in connection with the Russell diagram.

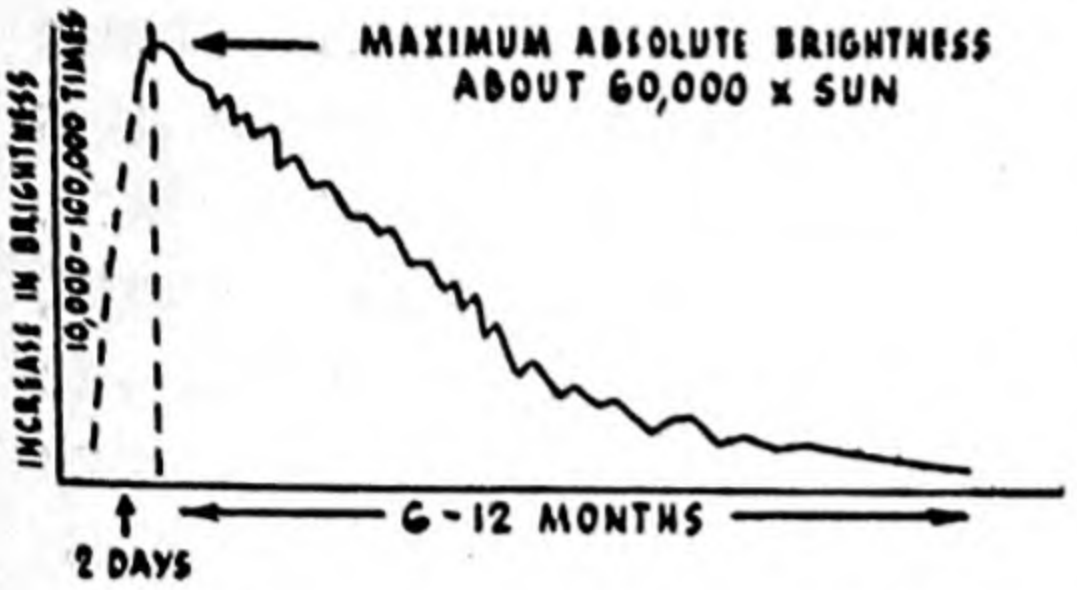
An explanation of the way in which this dense matter is produced is suggested by the modern nuclear theory of the atom. In their normal state, atoms are kept apart from each other and take up a considerable room because of the repulsion between their collections of electrons. It has been shown that, at very high pressures, the electrons may be stripped off, leaving the nuclei, which occupy only a minute volume. If this happened we might expect very dense matter to be possible, its state being a collection of completely ionized

atomic nuclei among which circulated the freed electrons which once were attached to them. This degenerate matter is most remarkable stuff and has excited the interest and controversy of scientists.

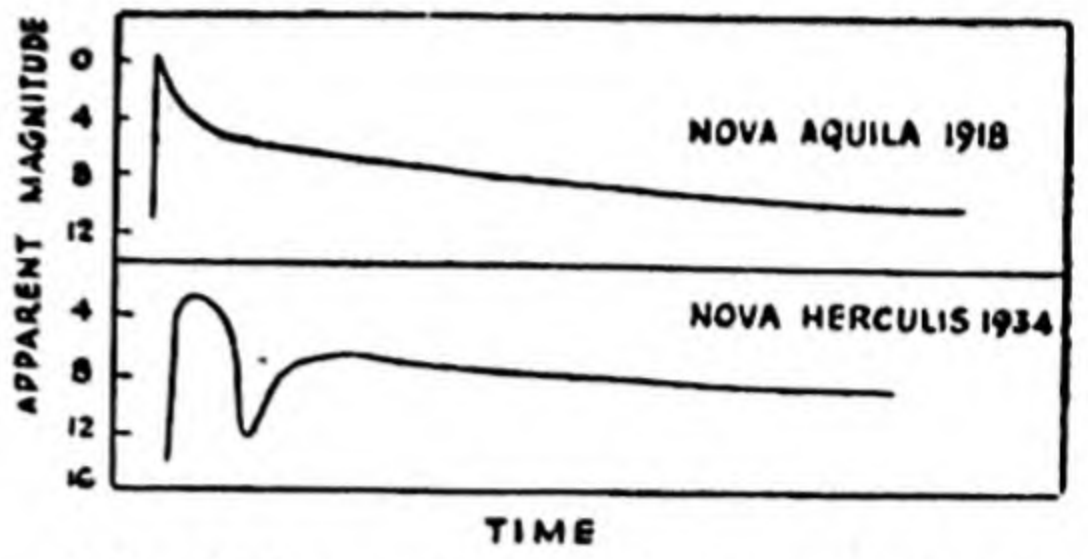
What is of even more interest is the question of how these stars ever came into being. In particular is this white dwarf stage a normal one for all stars? Some light has been thrown on this problem by an investigation of the late Sir Arthur Eddington's who determined, by a complex line of reasoning, how much hydrogen these stars contained. It will be remembered that stars generate their energy by converting their hydrogen into helium, so that, if the white dwarfs are, as might be conjectured, worn out stars at the end of their lives, then they ought to have used up all their hydrogen. This is not so. Eddington himself admitted that it was somewhat surprising that his results for hydrogen content came out between 0 per cent and 100 per cent, such were the difficulties of the investigation, but there does seem to be good reason for supposing that there are two sorts of white dwarf, one with a low hydrogen content, and the other, such as Sirius B, with over 60 per cent hydrogen. It is tempting to put the first sort of white dwarf at the end of stellar evolution—regarding them as worn-out stars with no hydrogen left—but how are we to fit in the white dwarfs which look worn out but still apparently have a positively brimming fuel tank? Before we answer this question, or to be more exact, before we describe the tentative theories which have been put forward, we must introduce some more members of our gallery of oddities.

The first are the so-called Novæ, or new stars, a name which could hardly be more misleading. These stars got their name because of their usual mode of discovery. A star is suddenly seen at a point in the sky where no star was before. For a star to have a reasonable chance of being observed in this way it must be visible to the naked eye, or lie not far below the limit of unaided vision. Discoveries of this kind are often made by amateur astronomers, particularly those interested in meteors, who from the nature of their hobby have a knowledge of the naked-eye stars which most professional astronomers can never hope to attain. Nowadays, too, their presence is detected on the Harvard sky plates—photographs of the

Fig. 32. NOVAE



(1) *The general characteristics of light variation of novae.*



(2) *Light curves of two famous novae, after Payne Gaposchkin and Gaposchkin.*

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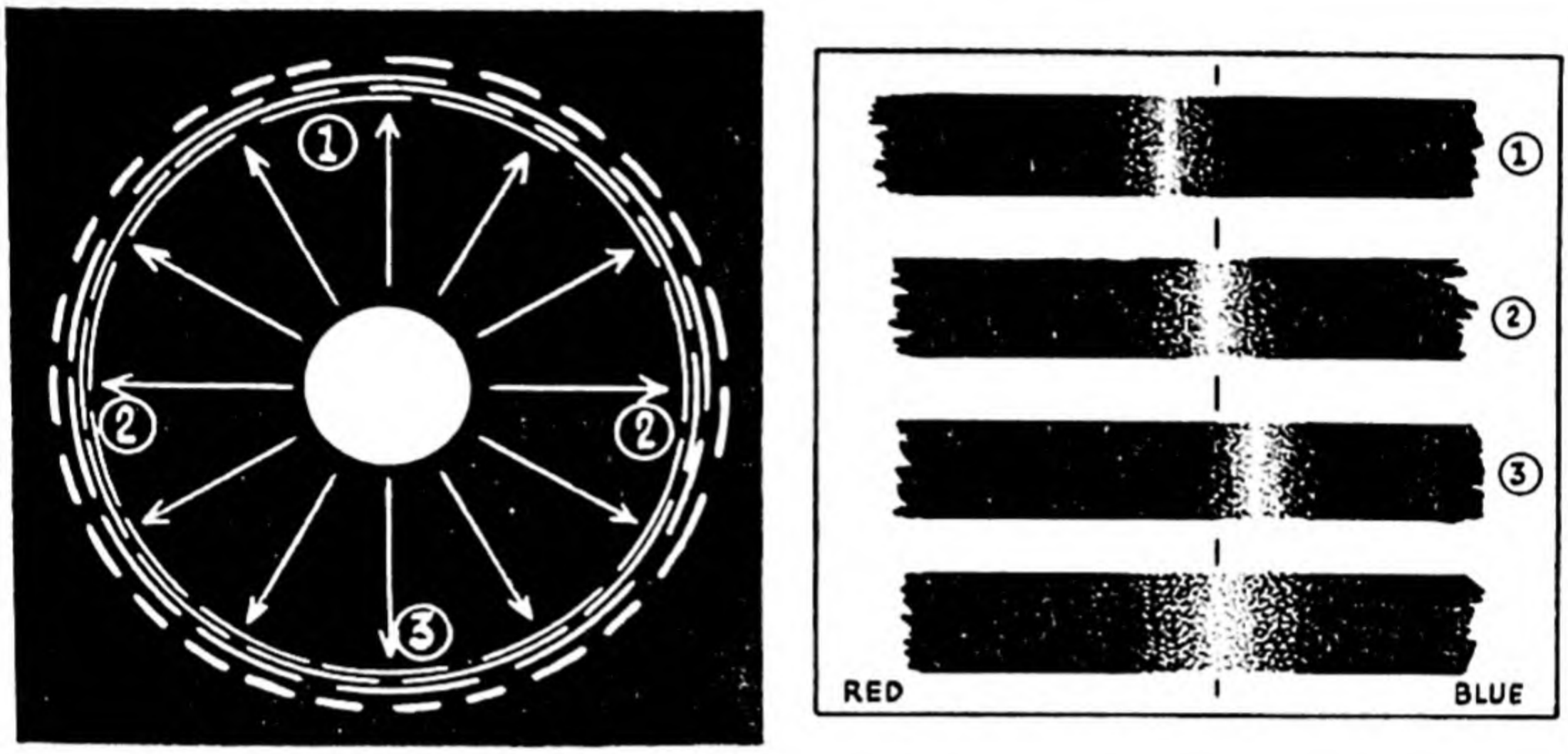
whole sky taken every two days. What has happened of course, is not the creation of a star, but the sudden brightening of a star previously too faint to be seen. It is often difficult to identify which of the many faint stars in a given region has suffered this catastrophe, and it is even rarer for any observations to have been made of such a star before the outburst when it bore no traces of the strange destiny in store for it.

The nova outburst is of a completely explosive kind. It may take only two or three days for such a star to increase its brightness by something like a hundred thousand times. Naturally we do not know the exact ratio since we are usually ignorant of the star's previous brightness, but the final true brightness (absolute magnitude) attained by such a star is round about -7, i.e. 12 magnitudes brighter than the sun or 60,000 times as bright. The increase in brightness is rapid. After the maximum has been reached the nova begins to grow fainter and usually dies away, perhaps with minor fluctuations, over the course of six months or a year. Novæ visible to the naked eye occur once every year or two, and they almost all follow the same sort of development, though there have been cases, such as that of Nova Herculis, 1934, where a second outburst has occurred. In the end, the nova usually fades from sight once more and is visible only with telescopic aid, although now, of course, its past history marks it out for special attention from all the thousands of equally faint stars. The spectroscope can tell us most about what is really happening to such a star, although as is to be expected, we have, with one exception, no observations of the really early stages of a

nova. It seems that a nova actually explodes: for some reason its supply of radiant energy undergoes a sudden increase and becomes too great for the mass of material which it is supporting. A huge shell of gas is thrown off from the surface, forming an expanding sphere. We cannot see this directly, but we can see that at the time of maximum and later, the spectrum shows all the signs of originating in gas at a very high temperature indeed. In addition all the spectrum lines, which because of the conditions of formation, appear bright, are very much broadened. We have seen that if an incandescent source is moving towards or away from us its spectrum lines will be displaced to the red or the blue respectively. If we are looking at a huge expanding shell of gas, moving outwards at something like 1,000 kilometres per second, then the light from the nearer portion of this shell, which is moving towards us, will be displaced to the blue. The light from the edge of the shell, which is moving directly across our line of vision, will not be displaced at all, while that from the farther part—the opposite half—of the shell will be moving away from us. Put all these components together, and the result is that the spectrum lines from an expanding shell of gas are enormously broadened, and this is just what we observe in a nova after maximum (Fig. 33). In some novæ a succession of shells may be thrown off the surface of the star: the spectrum may get more and more complex. The great breadth of these bright bands renders them most difficult to assign to any particular element: the high degree of ionization means that even if the spectrum were not blurred almost out of recognition by the broadening resulting from the motion of the gases, it might be a difficult matter to assign the lines to their true sources. There is, in fact, a certain resemblance between some of the conditions met with in novæ and those met with in the solar corona, but this similarity must not be pressed too far. If we are asked why a star becomes a nova we can only give the general answer that for some reason the energy production must have undergone a very large increase and have become too much for the stability of the star, and any more detailed explanation which may be given in the future must be based on a consideration of energy generation by subatomic changes. The ultimate fate of a nova is equally

Fig. 33. THE SPECTRUM OF A NOVA



Shells of hot gases are thrown out from the surface of the star. At (1) the gases are moving away and the spectrum lines are displaced to the red. At (2) the gases are moving across the line of sight, and the spectrum of these gases shows no displacement. At (3) the gases are moving towards the observer and the spectrum is displaced to the blue. The spectrum of the whole shell is produced by the superposition of all these contributions and consists of broad bright bands.

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unknown. If a nova is in fact surrounded by an expanding shell of gas it may be hoped that eventually this will grow sufficiently large to be visible. In general the wait will be a long one, for the rate of expansion becomes less catastrophic as the gases acquire more room, but it may not have to be measured in thousands of years. For instance Nova Herculis, 1934, had already acquired by 1940 a cloud of gas large enough to be seen as a small patch of luminosity measuring about three seconds of arc across.

Stars surrounded by such extensive gaseous shells are encountered (Plate VII). They are known as 'planetary nebulæ' a complete misnomer based on their appearance in small telescopes, and are really very hot bright stars surrounded by deep shells of tenuous gas which are still expanding rather slowly. The expansion is just such as might be expected in a nova grown subdued with age. The spectrum of these objects is remarkably like that of novæ. There is an almost overwhelming temptation to say that these must be the last stage of novæ, but there is a serious snag. Only about 150

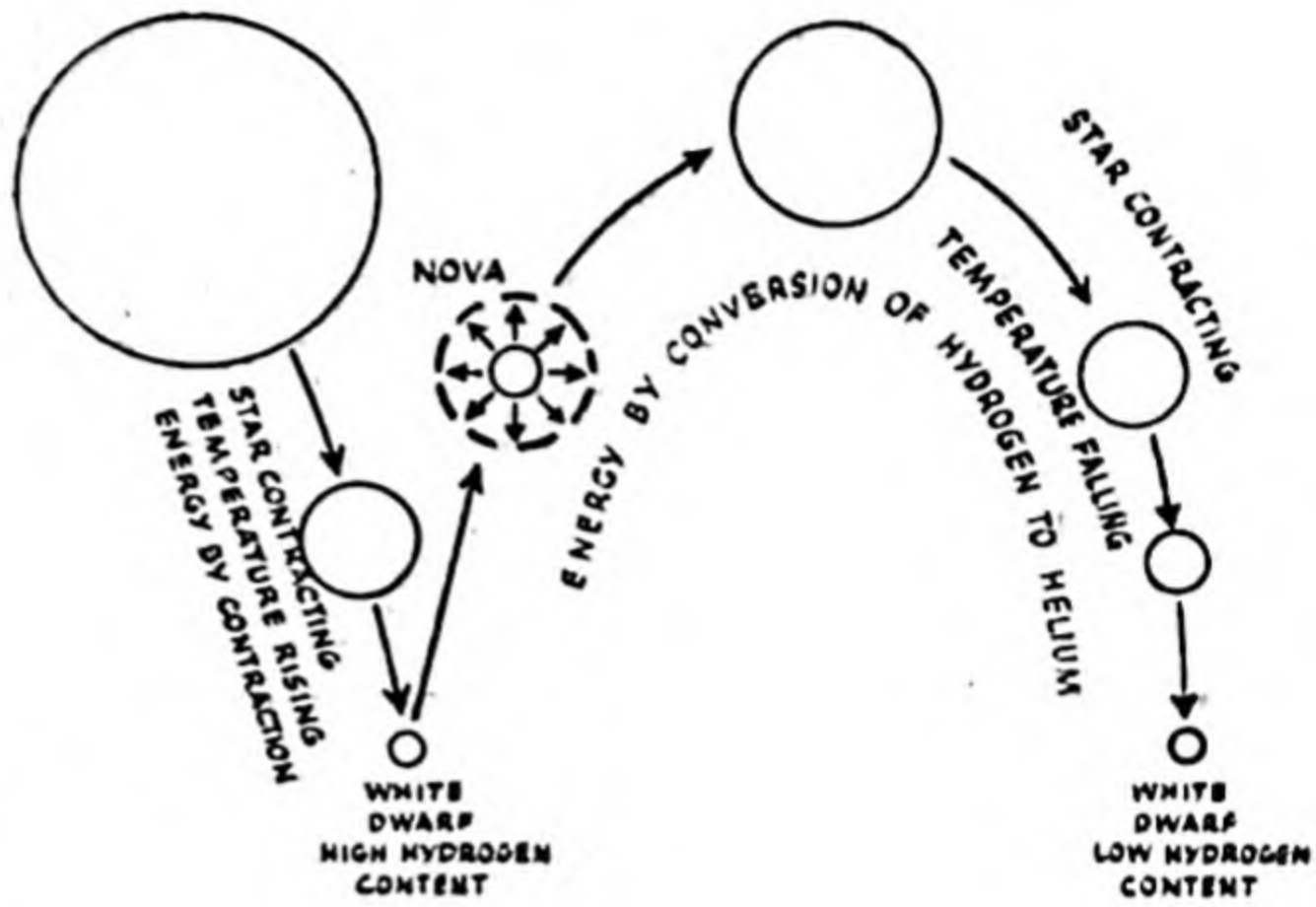
planetary nebulæ are known—enough for something less than a century's supply of novæ. Either the planetary nebulæ must be impermanent and change into some less striking kind of star, or they are not the last stage of novæ. A full explanation is lacking, but a purely personal opinion is that the resemblance is far too close to be an accident. If Shakespeare did not write the plays it must have been someone else of the same name: if a nova does not turn into a planetary nebula it must at least look exactly like one.

Having described the novæ, we must refer to a suggestion put forward by the late Sir Arthur Eddington, for fitting the white dwarfs into the sequence of stellar evolution. He suggested that the stars at first were practically pure hydrogen, in the form of large and tenuous globes. These shrank, and in so doing became hotter and began to radiate light. Finally they collapsed so far as to become white dwarfs with a high hydrogen content. Next he thought of atomic processes going on in the interior which would lead to the production of carbon and nitrogen (about one atom per star would be needed to set the process going) which would start the star off on its normal mode of energy generation—the conversion of hydrogen into helium using carbon and nitrogen as catalysts. This would be very rapid at first, and would occur with explosive violence, the star would become a nova, but would eventually settle down into a normal main-sequence star growing smaller and using up its hydrogen, and finally ending as a white dwarf with a low hydrogen content. In this theory the nova stage and two white dwarf stages are normal features of a star's history. The idea is attractive but at present there is no way of proving its truth or falsity particularly in view of the paucity and uncertainty of theory and observation of white dwarfs (Fig. 34).

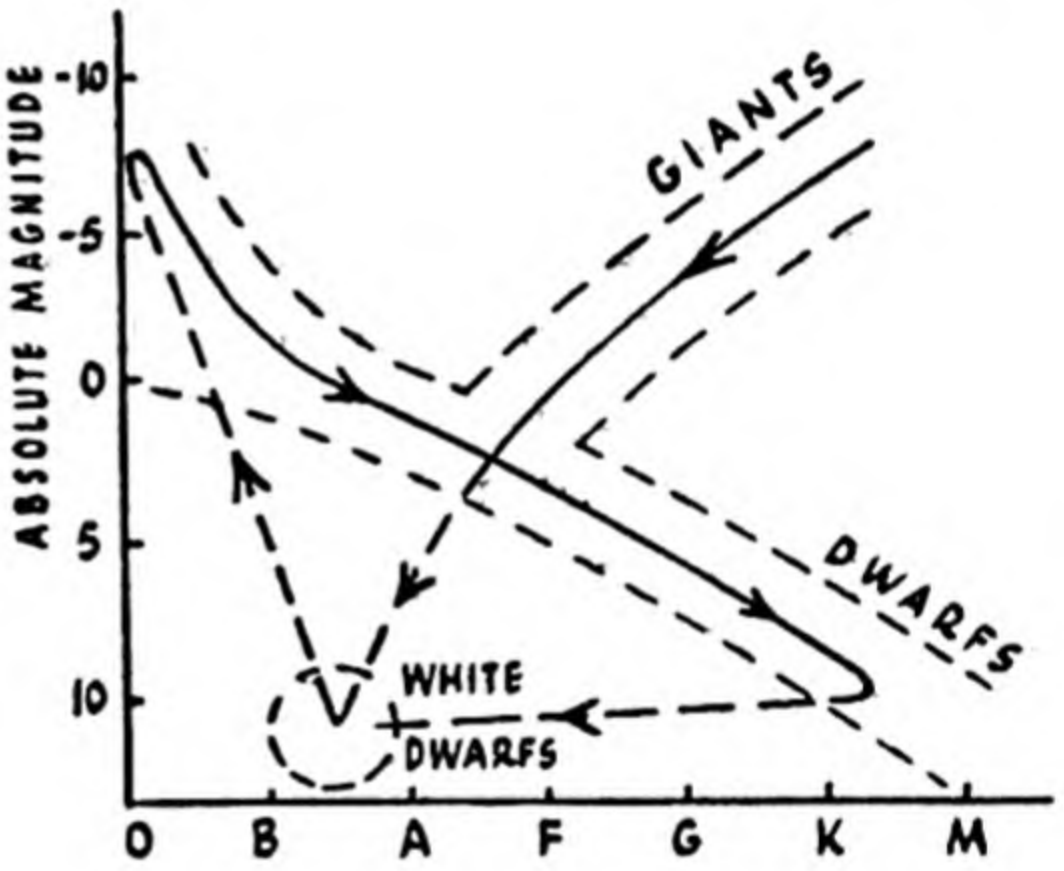
We have a good deal of observational knowledge of novæ, some of it, like the superb collection of spectra of Nova Herculis, of a most impressive kind. To many astronomers, however, the most important thing about a nova is that its maximum brightness is at about absolute magnitude −7. If therefore you were to see a nova anywhere in the universe, you could make a pretty good guess at its distance by seeing how bright it looked at its brightest, and using the fact that

Fig. 34. STELLAR EVOLUTION

No satisfactory account of stellar evolution has been given. One suggestion is shown in (1). The star contracts to a small diameter and becomes hotter. It becomes a white dwarf with abundant hydrogen. Atomic transmutation begins and the star becomes a nova later growing cooler and smaller as it uses up its hydrogen. It ends as a white dwarf with a low hydrogen content. The corresponding track on the Russell diagram is shown in (2).



(1)



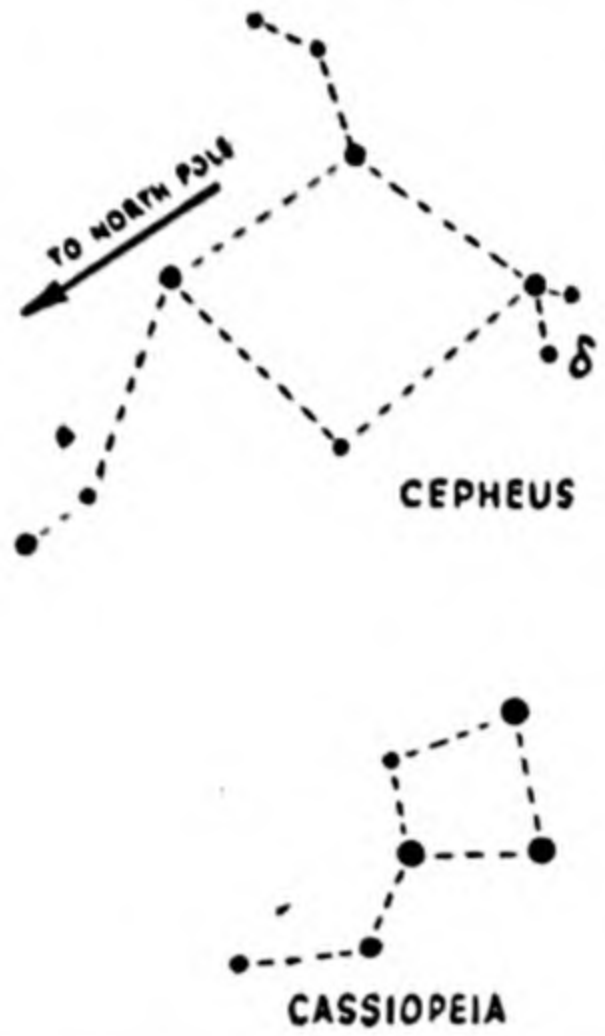
(2)

its real (absolute) magnitude is round about −7. This is a fairly high output of radiation, but something even stronger and visible at even greater distances would be a help. Nature has provided us with this in the supernovæ. In many ways these stars look like novæ on a bigger scale. They brighten up suddenly and die away slowly. Their spectra are those of an extremely hot gas, the lines are broadened and many of the spectral features cannot be ascribed to any known source. The velocity of ejection of the gases is about 3,000 kilometres per second. The absolute magnitude of a supernova is round about −14, or about 40 million times as bright as the sun. But the resemblance is superficial. There is no continuous gradation of properties from novæ to supernovæ. The supernovæ are an entirely separate class and we know less about

their origin than we do about novæ. Supernovæ are comparatively rare, but owing to their great brightness we can see them even at the greatest distances to which modern telescopes can penetrate. We may be restricted to distances within ten parsecs for our observation of faint stars like white dwarfs, but we have a whole universe full of supernovæ to study. A whole universe full of supernovæ is not many. At the beginning of the war something like a dozen supernovæ had been observed, most of them in distant systems of stars. Two supernovæ are known to have occurred within our own galaxy or star system. One of these occurred in 1054 and is recorded by the Chinese and Japanese astronomers of the time, and the other happened in 1572 and was observed by Tycho Brahe the early Danish astronomer. These two seem to have been bright enough to be visible in the daytime. In 1885 a nova, presumably a supernova, occurred in the Andromeda nebula, the nearest star system to our own. In the case of the first two supernovæ we know what the outcome was. In both cases large gas clouds have been identified as near as we can judge at the positions of the supernovæ, and it appears that these gas clouds are the débris of the possibly completely disrupted supernovæ. Although we know even less about supernovæ than we do about ordinary novæ their great brightness which renders them visible in the furthest depths of space makes them extremely useful for estimating the very largest astronomical distances.

This same type of usefulness is exhibited in an even more precise way by a certain class of stars whose output of radiation, while not so disastrously outside their capacity for management as it is in the case of the novæ, is nevertheless not quite in balance with the quantity of material in the star. As we have seen: float too much matter on your radiation and your star will collapse in self-defence. Put too little and it will blow itself up. It may quite well happen that the star overdoes both the collapsing and the blowing up process, so that when it has collapsed it is ready to expand again; and when fully expanded is ripe for collapse. If this is so the result will be a pulsating star, alternately expanding and contracting with its light varying in consequence. We have already seen that one type of variable star can be produced by the

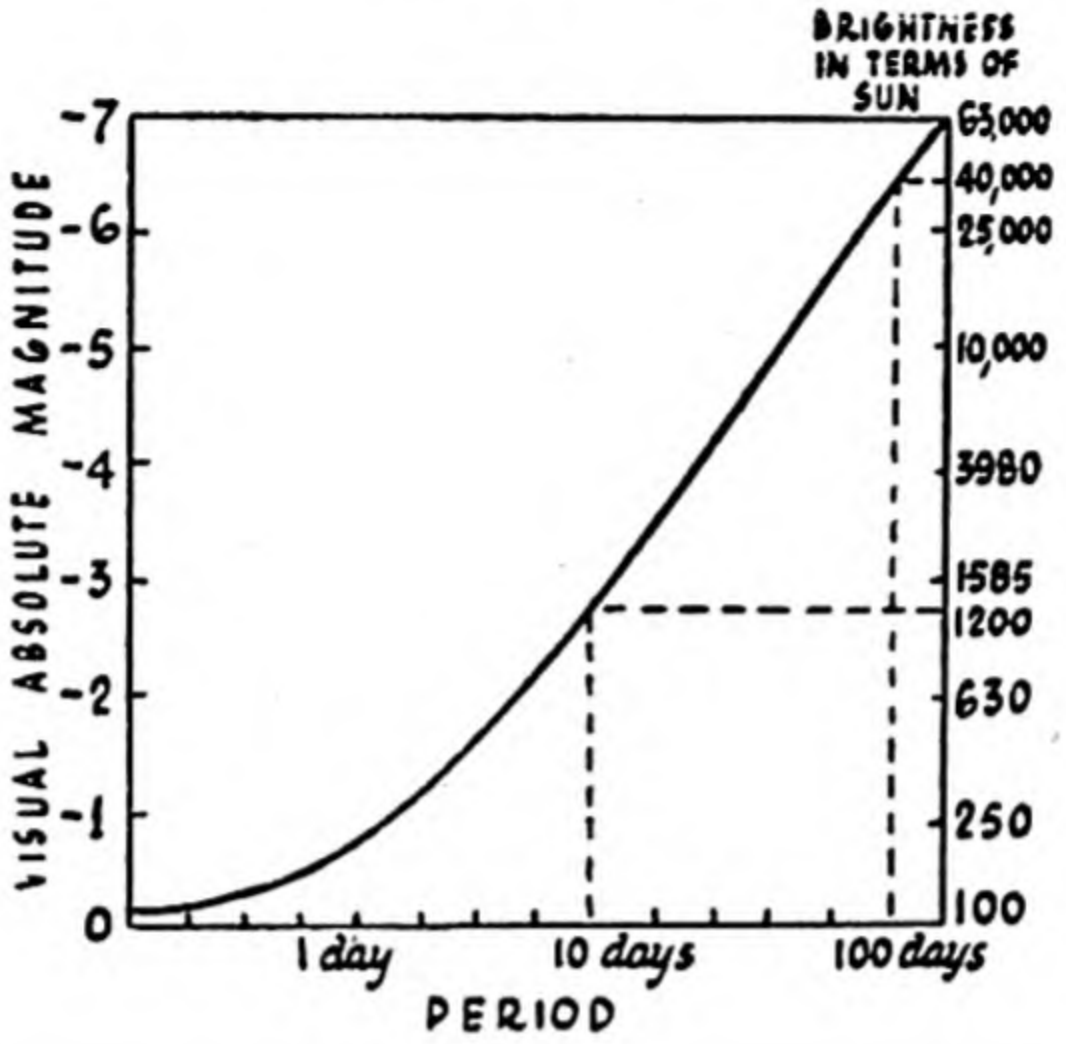
Fig. 35. RECOGNITION CHART FOR δ CEPHEI



shutter effect of one member of a pair of stars passing in front of the other. Now we are concerned with a real variation in the star itself.

There are a great many of these intrinsic variables, and it may be that our own sun, exhibiting a periodicity of eleven years in its spottedness is one example of an intrinsic variable in which there is no pulsation of the star. Variable stars of a bewildering variety are known. Some of them are quite regular in their variation and follow exactly the same course time after time. Others are less clock-like in their variation while others exhibit no regularity of any kind. We can hardly attempt to list all the varieties of intrinsic variable, and it must be added that except in one particular type we have nothing in the nature of reliable theoretical knowledge of what is going on. As may be expected, the particular type of variable star of which we have some fairly reliable knowledge is a type which varies regularly and which is known as the Cepheid variables after the prototype, Delta Cephei. To put the cart before the horse we must say that this particular type of star is believed to be pulsating in the way in which we have indicated. It is not surprising that the bigger stars of this type are pulsating slower than the smaller and fainter ones, just as machinery with heavy reciprocating parts usually is slow moving, whereas high-speed machinery is usually small and light. Extensive theoretical discussions have been made

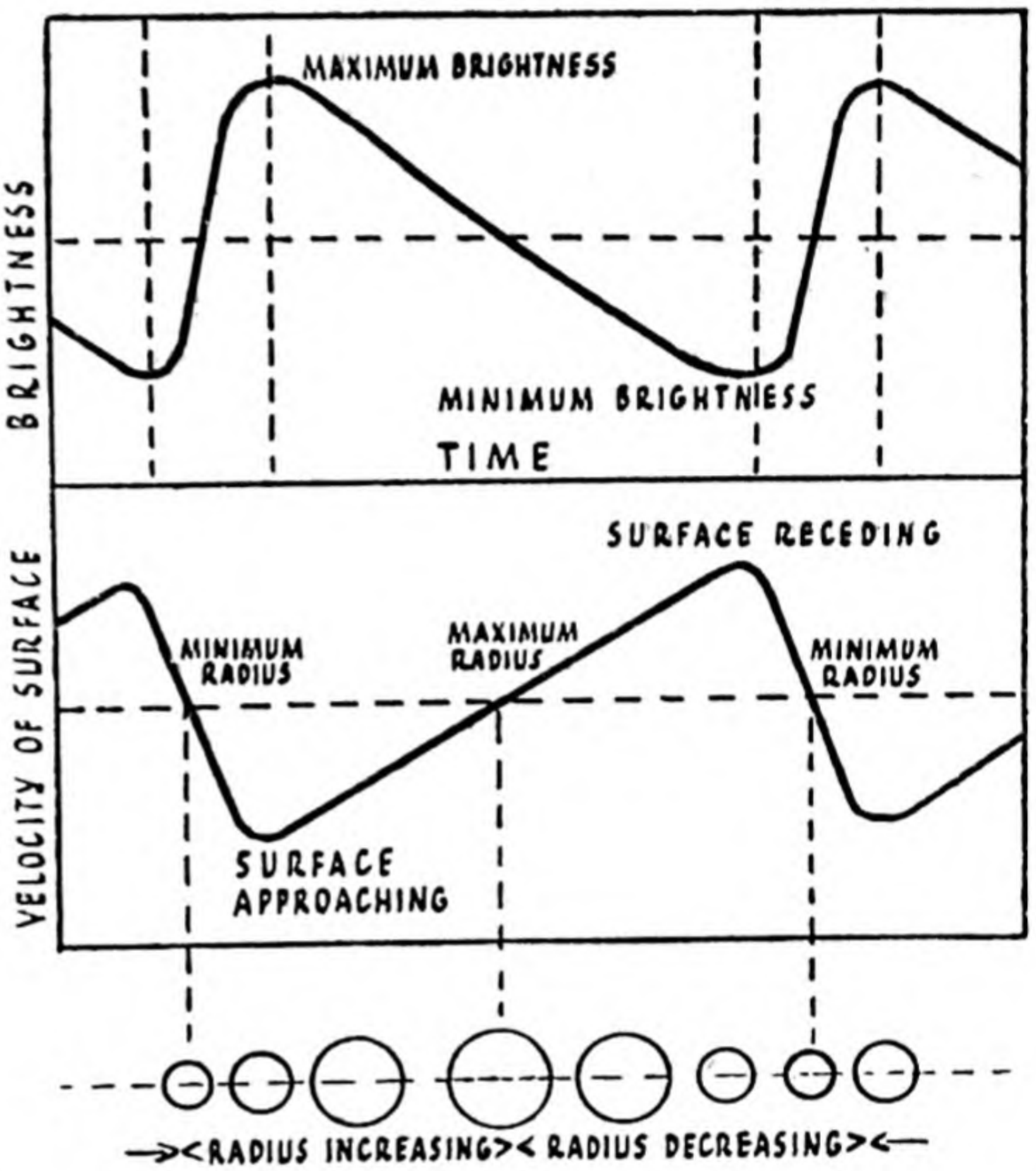
Fig. 36. THE PERIOD-LUMINOSITY RELATION FOR CEPHEID VARIABLES



of this type of star, especially in relation to an anomaly which has been observed. Most of these discussions have assumed that these stars are pulsating symmetrically, that is that they remain spherical, but expand and contract, but mention must also be made of an alternative theory recently advanced which suggests that in effect, the bulging is not symmetrical, but that we have to deal with a star having a bulge or rather a pair of bulges, running round and round on its surface.

As far as the relation between the rate of pulsation and the brightness is concerned, observation and theory agree admirably. As long ago as 1913 Miss Leavitt of Harvard observed a number of Cepheid variables in a group of stars known as the Lesser Magellanic Cloud. Cepheids are intrinsically very bright stars and so they were readily observable although this group is too far off (about 30,000 parsecs) for its parallax to be determined directly. However, the important thing was that they were all at the same distance, so that, even though this distance could not be measured at that time, a Cepheid in the cloud which looked brighter than its neighbour really was brighter. Miss Leavitt made a graph showing the relation between the brightness of the Cepheids and their rate of variation. We now know that a Cepheid which varies in, say, 100 days is actually 40,000 times brighter than our sun, whereas one which varies in 10 days is about 1,200 times as bright as

Fig. 37. CEPHEID VARIABLES



The most satisfactory theory is that these stars are pulsating. The figures show typical light curves and velocity curves. The chief difficulty is that the two curves are not in step and much of the work on Cepheids has been concerned with attempts to explain this.

the sun. This relation appears to be universally true, and, since Cepheids are found in all the groups of stars which have been observed, and since in addition they can be seen at very great distances and their characteristic manner of variation makes them easily recognizable, they are most useful as indicators of distance. All one has to do is to find out how rapid their variation is: to read off from the curve (Fig. 36) their absolute magnitude, and then to put them at such a distance that they become as faint as they look when seen from the earth.

Direct evidence is available that these stars do pulsate. When the star is expanding its surface is moving up towards us, and the spectrum lines of the star are displaced to the blue. When the star is collapsing the surface movement displaces the lines to the red. The anomaly mentioned above is that contrary to expectation, the star is not brightest when it is largest (Fig. 37). A variety of suggestions has been advanced to

account for this. One is that the flow of radiation takes time to get from the inside of the star to the outside: the star must heat up its own material before it has any radiation to spare for outside space; another is based on the suggestion already mentioned which may roughly be put in the form that the expansion and contraction of the star are not uniform, but that a pair of excrescences or bulges move over its surface.

This collection of oddities includes only the more respectable black sheep. Stars exist whose construction is much more peculiar than any of these. There are, for example, binary stars (pairs of stars moving round one another under their gravitational attraction) in which there are marked peculiarities of spectrum, some of which can be accounted for by the fact that the stars are so close that they pull each other into egg-shaped masses, or that when one star is behind the other, the part of the light of one is seen through the gas clouds of the other, a state of affairs which produces a most complex spectrum. Then there are the super-hot stars with very extended atmospheres: the super-heavy giant stars discovered by Trumpler: the excessively cool and red stars which are only just above the melting-point of platinum and so on in endless variety. But these are arrangements of stars on paper: we have arbitrarily sorted them out into different kinds. What is more important is to discuss how these various types of stars are arranged in space, and how they are gathered together in groups and clusters.

Chapter Eight

GROUPS, CLUSTERS AND COLLECTIONS

WE have now developed a fairly good system for the investigation of stars. Dealing with them singly we can find their distances, their motions, their temperatures, sizes and so on. However, so far we have not considered at all how these stars are arranged in space. Are they spread out uniformly, or do they appear in groups, and if the latter, is there anything which we can say about these groups?

We can start from a fact of observation accessible to the naked eye. The stars appear to be scattered around the sky in a completely irregular manner. With sufficient imagination, the brighter ones can be split up into convenient groups in which the eye of faith can distinguish a likeness to birds, beasts and other creatures. It is worth noticing that no part of the sky is absolutely devoid of stars. There may not seem to be much system about the arrangement of the stars, but we are at any rate pretty well surrounded by them. On turning our attention to fainter stars, including, say, even those which can be seen in a pair of field-glasses, it becomes possible for us to distinguish certain regularities in the distribution. There is a strip of the sky in which very many stars can be seen—this is the Milky Way—and if we turn our attention to the sky at right angles to the Milky Way, we can see very few stars (Fig. 38). The clue to this phenomenon was first suggested by Thomas Wright in 1782 in his 'grindstone theory of the universe' and it was put on to a firm numerical footing by the work of the two Herschels, father and son, in the early nineteenth century.

The modern view, which has become consolidated in the last twenty years, is that the sun, and of course, its attendant planets, belong to a huge flattened system of stars, without definite boundaries, which is about 30,000 parsecs across and about 3,000 parsecs thick. Herschel thought that we and our sun were near the centre, but the modern view is that we are

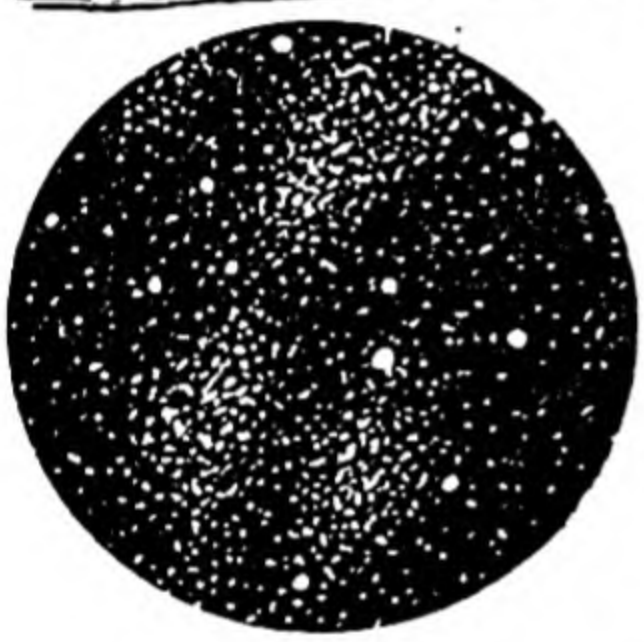


Fig. 38.

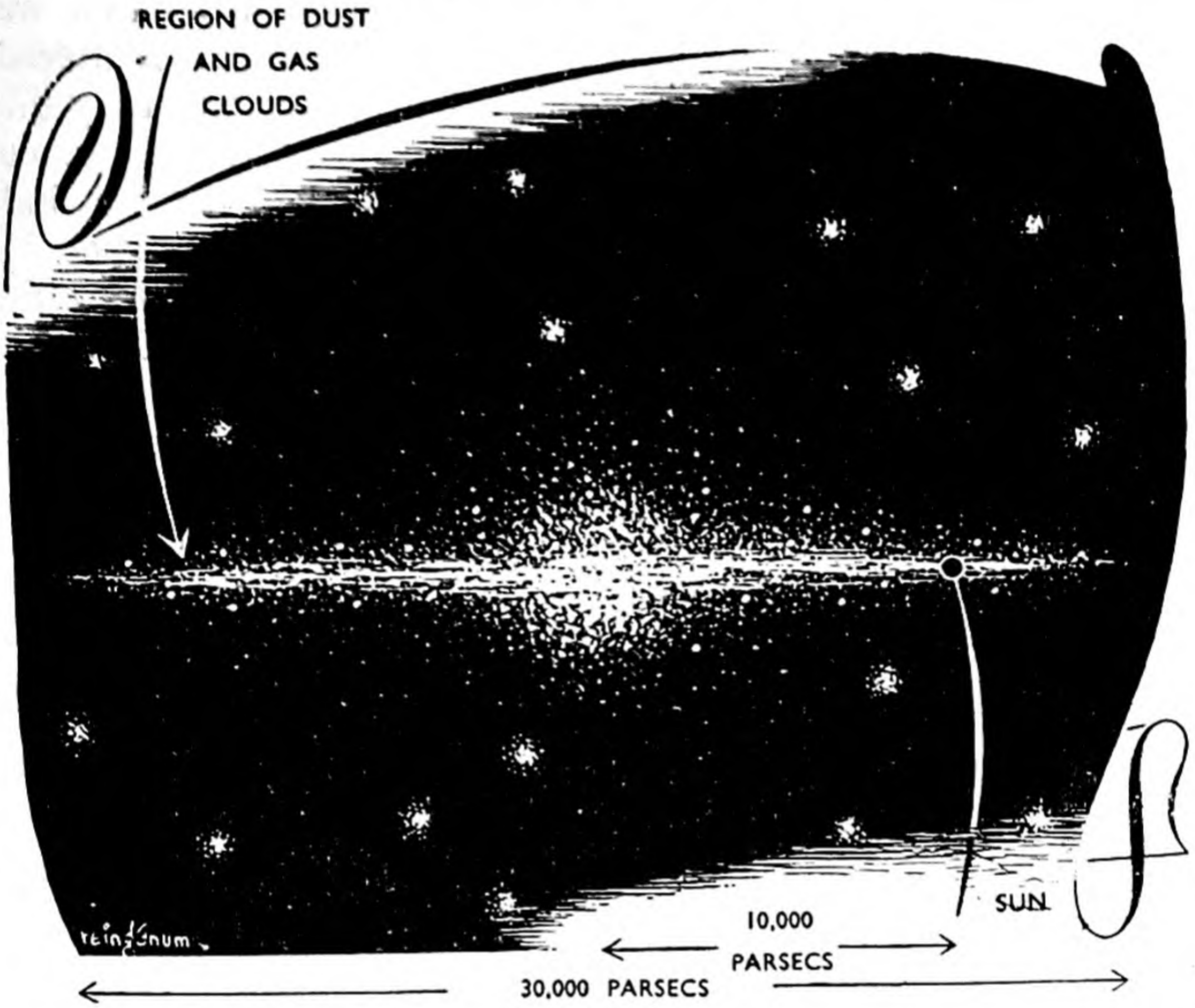
LOOKING AT

THE

MILKY WAY

fairly near the edge, at a distance of about 10,000 parsecs from the centre (Fig. 39). We can see how this idea gives us a correct picture of our sky. When we look towards the centre of the system, which is in the constellation Sagittarius, (about 10° east of the bright star Antares), very many stars are visible, whereas if we look in a direction at right angles to the plane of the system the stars are less dense and the delicate light of the millions of stars which comprise the system (the Galaxy) is missing. Thus it is easy to see that our view of the Galaxy will be of a fairly narrow band within which stars are very numerous, their numbers falling off on both sides of it. One point which requires answering is that the Milky Way runs all round the sky in a complete circle. Surely when we look in a direction opposite to the centre, then we, being so near the edge, should see right out of the Galaxy into the empty space beyond? To make this clear we must get the scale correct. If we take a fairly average star, of, say, absolute magnitude zero, then if it is to look as faint as the tenth magnitude to us (well

Fig. 39. THE GALAXY

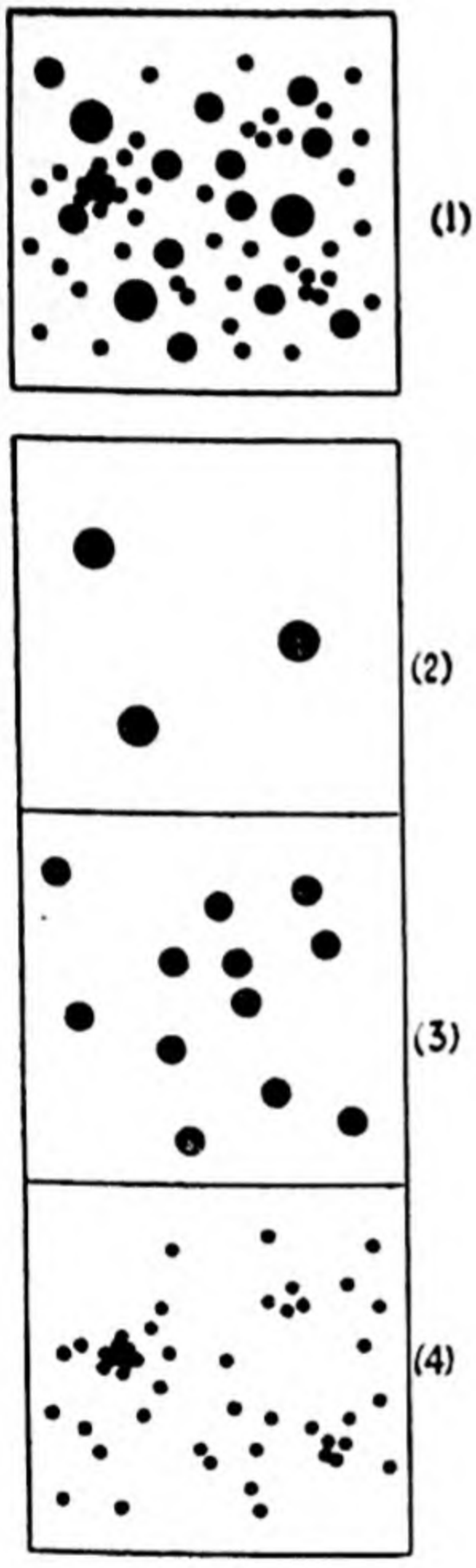


below the limit of unaided visibility) it must be about a thousand parsecs off. This is a great distance, but it is round about five thousand parsecs from our position to the edge of the Galaxy, which means that with the unaided eye and even with a pair of field-glasses we cannot see far enough into space to take us to the limits of the Galaxy in the plane of the Milky Way. On the other hand, in directions perpendicular to this plane the stars thin out very rapidly and our range of vision is great enough for us to miss the cloud of distant stars whose light forms the Milky Way. A second factor is that in the plane of the Milky Way there are extensive clouds of dust and gas, some of them illuminated by the stars in or near them, and others being dark. These clouds also play a part in limiting our effective range of vision and actually make the stars look fainter than they otherwise would. This point is worth emphasizing a little. If our eyes were less sensitive

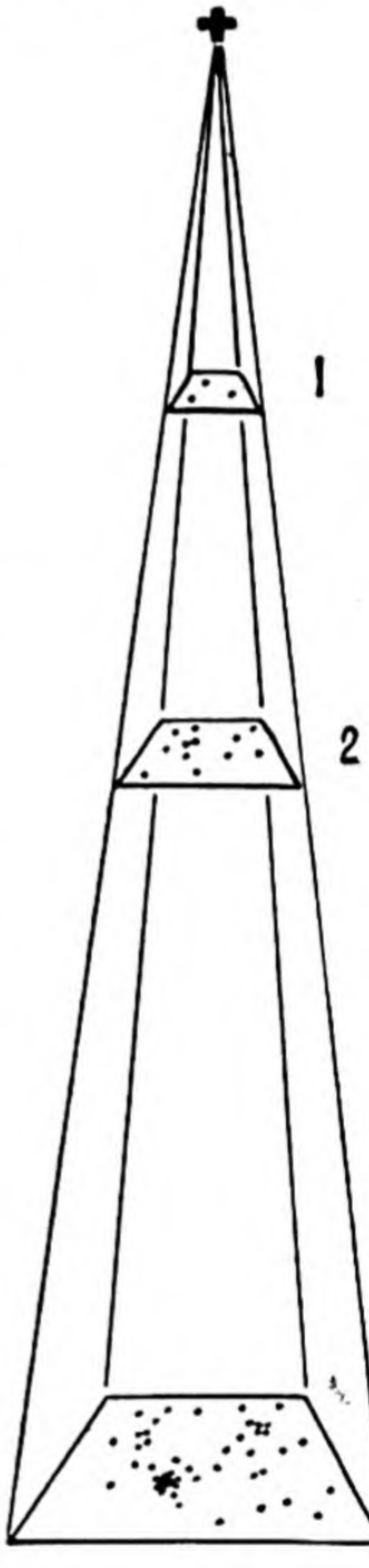
than they are, so that we were only conscious of the hundred brightest stars in the sky, we should be convinced that we were at the centre of the star system because these are scattered fairly uniformly over the whole sky. Only when we study the fainter stars and increase our range of vision to a distance comparable with the dimensions of the Galaxy do we find evidence that the star system does not extend indefinitely.

Herschel introduced exact numerical methods into this type of study and so founded the science of stellar statistics. Suppose we imagine for the moment that all stars are alike in brightness. Then a star will look faint because it is distant and bright because it is near to us. If we photograph a small area of sky we shall get stars of all brightnesses appearing on the plate, and, provided we assume that all of them are really of the same brightness, then it is easy to make a model of the actual distribution of the stars in space (Fig. 40). All the bright ones must be near to us, so we pick them out and put them in the model close to our own position. Then we sieve out all the stars which are, say, brighter than a quarter the brightness of the first class of stars. These must all lie at distances between one and two times the distance of the first set. What we do in fact is to sort our stars into classes according to their brightnesses, a process easily accomplished by counting them on the photographic plate, and each class has its own range of distances. Finally we cover the whole sky with photographs and do the same for each area. We should then end up with a model of our own stellar system. It is a scale model, but we do not know the scale: we can only expand it to the proper size when we know the distance in parsecs of some of our stars. It is also built on the assumption that all the stars are equal in brightness, and this is not even approximately true. As we have seen, the real brightnesses of the stars have a range of more than one hundred million to one, but even so, this model of ours constructed on this assumption of equal brightness, just as Herschel constructed it, looks quite like our modern version. The whole difficulty of the subject lies in the disentanglement of the effects of distance from those of real differences in brightness, and further, in taking account of the fact that the plane of the Galaxy contains so much obscuring matter. Since Herschel's time we have been dethroned from our place

Fig. 40. PLOTTING THE STARS IN SPACE



In a small area of sky (1) we see many stars of different brightness. If we assumed that all stars were really alike, they would appear bright because they were close to us. The bright stars (2) would be at a short distance (Position I): the intermediate stars (3) at an intermediate distance (Position II) and the faint stars (4) at a great distance (Position III). Actually the stars differ very much in brightness but the general picture obtained by this crude argument is not far from the truth.



at the centre of the Galaxy and moved out to the edge. At a much later date the effects of the obscuring matter were underestimated: stars are dimmed by intervening clouds of gas. If you neglect the gas you must move your star further off for it to look as faint as it does, and your galaxy will be too big. Again if you neglect these obscuring clouds it will appear that we are in a region where stars are very plentiful. Once they are taken into account, as was done in the work of the Dutch astronomer Oort just before the war, it appears that the contrary is true—that we are in fact in a region where stars are scarcer than they are in neighbouring regions. Ten years ago it was quite widely believed that we were in a specially

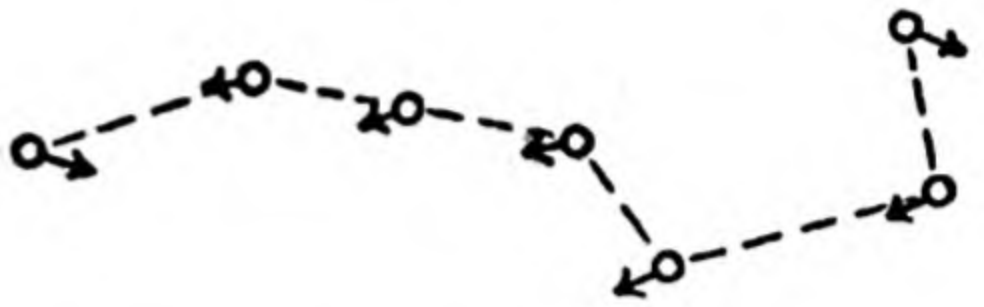
rich region, a member of a group of stars which was called the Local Cluster. This has now been abolished and is relegated to the graveyard of theories—some of them very valuable in their day—which did not explain all the facts.

We have had the temerity to give dimensions to our Galaxy, but it must not be thought that at a distance of 15,000 parsecs from the centre the stars just stop. On the contrary the system has no definite boundaries: the numbers of stars fall off gradually as one passes outwards. The system has an indefinite boundary and the stars straggle out thinner and thinner like the suburbs of London. Green spaces become more frequent as the centre is left behind, but no one can put a definite mark and say 'Here ends all that is dependent on Greater London.'

The Galaxy contains stars, and gas clouds, and the latter are most dense near its central plane. If we use an old analogy and liken the Galaxy to a bun-shaped system of stars (it is more like a currant bun with the bun removed and the currants left behind) then the gas clouds occupy the position of the butter when the bun is sliced and buttered. The term 'gas cloud' is possibly a misnomer. Certainly throughout the Galaxy there is a very tenuous cloud including atoms of calcium, sodium and hydrogen, and even, according to the latest research, atoms linked up into molecules, but it is probable that many of the clouds are dusty in nature and consist of fine solid particles. The effects of these two sorts of cloud on light passing through them are different enough to offer a hope of deciding on the constitution of any particular cloud. These clouds have been used in various ways. Light passing through them is not only dimmed but reddened. A star too red for its spectral type may therefore look fainter than it would if its light were not obscured by its passage through the intervening cloud. There is a relation between the reddening and the dimming which can be turned to account in deducing the dimming, and hence the distance, of the star from the reddening. Again, distant stars have imprinted on their spectra the lines of the calcium and sodium clouds through which their light has passed, and these inter-stellar lines can be measured and used both in estimating the distances of stars and in deducing a little about the condition of the intervening gas clouds.

Fig. 41. A MOVING CLUSTER

Some groups of stars, of which Ursa Major is one, are moving together through space.



But besides these clouds there are other members of our Galaxy. Here and there the uniformity of the star distribution is broken by the appearance of a cluster of stars. At great distances these can be seen as knots of stars, but even some of the nearer stars visible to the naked eye belong to clusters. The Pleiades is a real cluster of stars which are close to each other in space: the constellation of the Plough (Ursa Major) is another such cluster (Fig. 41). All the stars in the cluster are comparatively close in space and are moving through space together. Almost any astronomical photograph will show such knots or clusters of stars, and often, incidentally some of the gas clouds of which we have been speaking. These irregular clusters are within our own Galaxy and form as it were special objects of interest within it.

There is in addition a special type of cluster which is completely spherical in shape, and is known as a globular cluster. Like our own Galaxy it has no definite boundary, but if we drew contour lines or rather surfaces, marking off the places where the star density was say, one star per ten cubic parsecs, and so on, these contours would be spherical. These globular clusters are very much smaller than the Galaxy, being a few hundred parsecs across, as compared with a few tens of thousands for the Galaxy, and about one hundred of them are known. They are scattered about on the outer fringes of the Galaxy and define a roughly spherical volume around it. They are curiously similar in size and appearance and even in the details of their distribution of density, so that an unlabelled photograph of one (Plate VII) might easily be taken for almost any of them. Here again we have reached the frontier of astronomy for as yet, no one has given an account as to how these clusters must have originated or why they are found distributed as they are.

The last class of object to be mentioned as members of our

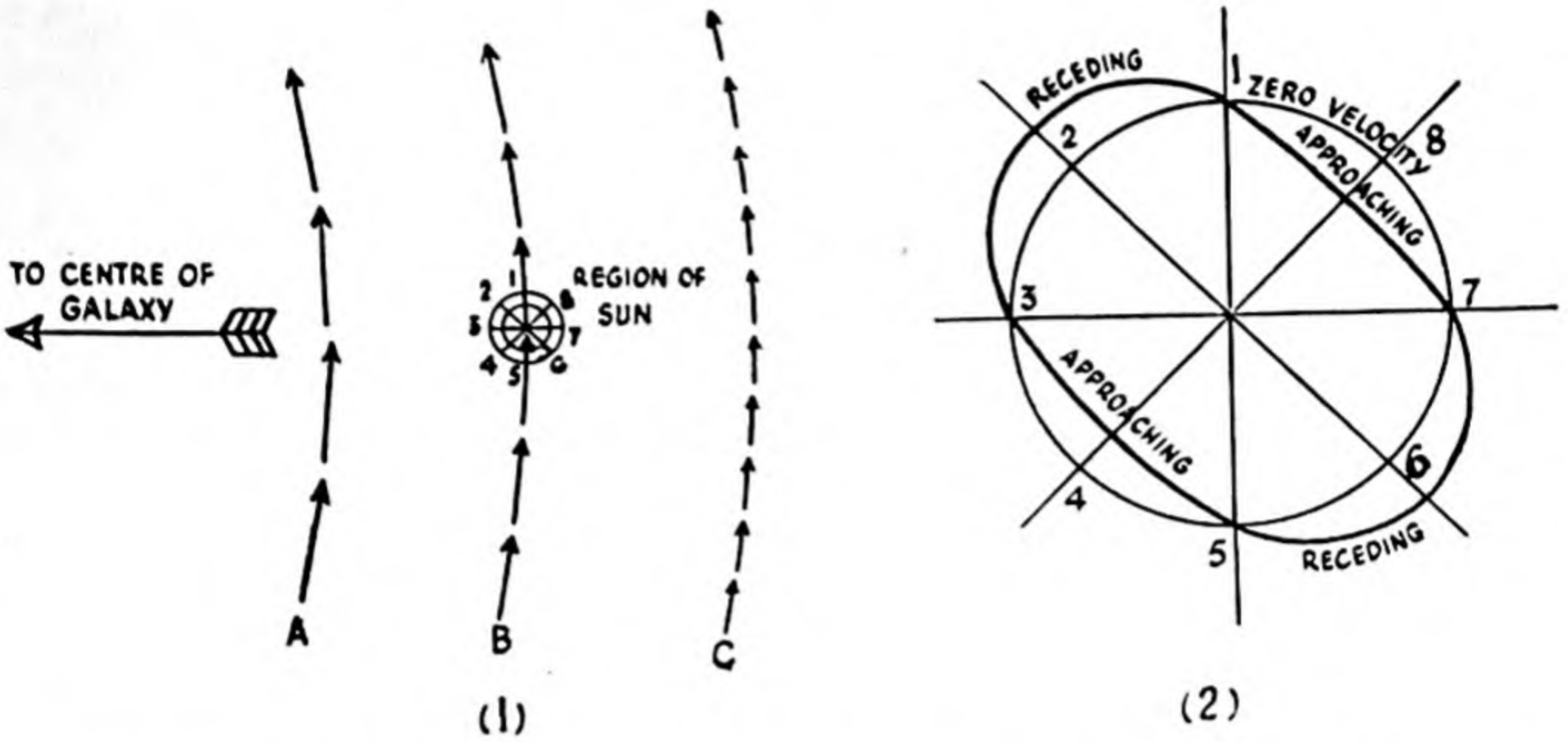
Galaxy are the 150-odd planetary nebulæ which we suspected (but acquitted under the Scottish verdict of 'Not Proven') of being ex-novæ. They are found more or less in the plane of the Milky Way and roughly uniformly distributed, but again their origin is unexplained.

There remains one very important property of the Galaxy to be described. It is its motion, and its importance lies in the fact that without motion the Galaxy could not continue to exist. If all the materials of the Galaxy—the stars, gas clouds, planetary nebulæ, clusters—were held in their present positions at rest relative to each other, and then were released, the whole system would fall together under its own gravitation. It is motion which keeps the solar system, binary star systems, and the Galaxy in being as extended objects. It is impossible to summarize here all the complex researches which have led up to our present view of the Galaxy. All we can do is to state the results.

First of all, the Galaxy is rotating, not as a solid body but in the same way as the solar system. The rim of a wheel moves faster than its centre. The outer planets move slower than the inner. The outermost stars of the Galaxy move slower than the inner ones. Here we must add a word of warning. We are for the moment thinking on a big scale, not even in terms of individual stars, but in terms of groups of stars. What we must say is that a group or cluster of stars near the edge of the Galaxy is moving round the centre of the Galaxy at a lower speed than one nearer the centre. It is perhaps convenient to think of such a group as a real knot of stars visible on a photograph, but we can, equally well, separate out a small volume of space and consider all the stars within it. For example, we may have occasion to speak of the stars in the neighbourhood of the sun, by which we should mean all the stars in a sphere of, say, 250 parsecs radius, drawn with the sun as centre.

What we are considering in fact is a general tendency of motion. Each of these groups is like a cloud of gnats in which each gnat goes about his business hither and thither, but the group as a whole advances steadily. This is the most useful way of thinking of the motion of the Galaxy as a whole, and additional point is lent to it by the fact that the stray individual

Fig. 42. THE ROTATION OF THE GALAXY



The galaxy rotates, not as a rigid body, but slower at the edge than the centre. The consequences of this can be detected, and enable us to infer rotation, even though the sun is taking part in the movement. In diagram (1) groups of stars at different distances from the centre are shown moving in circular orbits. Those at A move fastest (long arrows), those at C slowest (short arrows). An observer on the earth makes a compass card diagram and notes whether the stars which he sees in each direction are moving towards him or away from him. In directions 1 and 5 the stars are moving at the same speed as those near the sun; neither gaining nor losing. On his diagram (2) the observer notes this as zero velocity. In directions 3 and 7, the stars at A and C are moving across his line of sight, i.e. they are neither approaching nor receding. These facts are also marked on diagram (2). In direction 2 the stars A are gaining on those in B and so appear to be receding; in direction 6, the sun is gaining on those at C, so that these also are receding. In direction 4, A is gaining on B, while in direction 8, B is gaining on C; hence in both these directions the stars seem to be approaching. By filling in intermediate directions the observer can construct the oval curve in diagram (2) where the radius in any direction indicates the velocity of approach or recession of stars seen in that direction. A velocity variation of this kind is actually observed, so that diagram (1) is thought to be a correct picture of the rotation of the galaxy.

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motions of the gnats or stars in each group are much slower than the general motion of the group.

This slowing down of the motion at the edge of the Galaxy has the interesting consequence that stars outside our group are falling behind us, and those nearer the centre are gaining on us. Those dead ahead and dead astern are following round the same track as ourselves and at the same speed, so they neither gain nor lose. It follows then, that as we run our eyes round the Galaxy, we shall see a regular variation

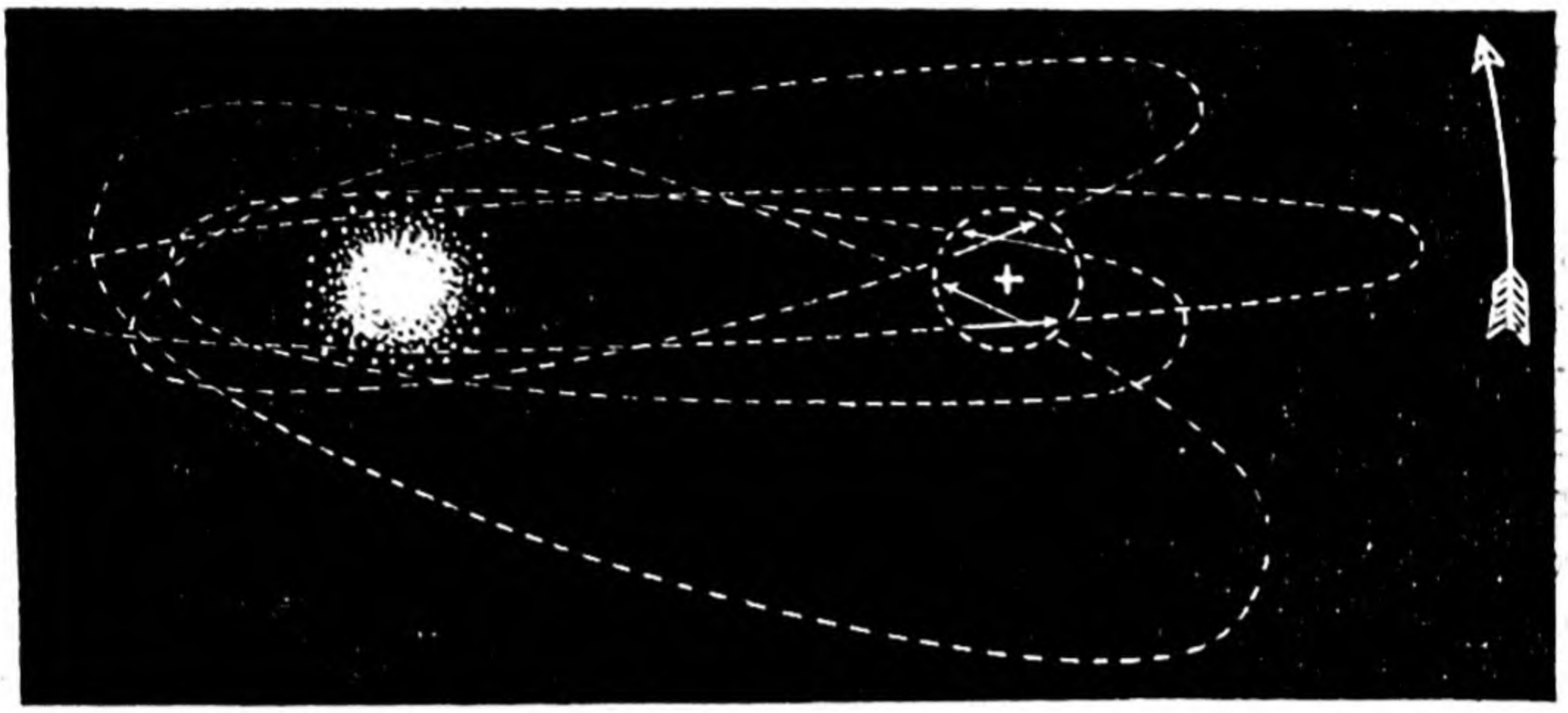
in the velocities of the various groups of stars (apart from their individual stray motions which cancel out when we consider a whole group) and it was this regular variation which led to the present picture of the motion of the Galaxy (Fig. 42).

It is time we let the cat out of the bag and admitted that our Galaxy is not unique. There are millions of others like it scattered throughout space. We must introduce them here, because the only direct way of discovering how fast the stars in the neighbourhood of the sun are moving is to observe something not taking part in that motion. The problem is complicated by the fact that the Galaxies are moving themselves, but in a fairly systematic way, and by observing their speeds of approach or recession by means of the spectroscope it has been deduced that the sun is moving round the centre of the Galaxy with a speed of something like 400 kilometres per second. It takes us at that rate 250 million years to make a complete circuit. This is a surprisingly short time for it means that the sun and its attendant earth have been round three or four times in known geological epochs. It is also part of the reason why the local cluster (now abolished) proved such a puzzle. If an extensive cluster of this kind did exist, then since its outer edge would be moving slower than its inner, it would gradually be stretched out until no semblance of a cluster existed, and after only one revolution its dispersal would have been fairly complete. Now that the existence of a local cluster has been disproved, we have the problem that the sun appears to be in a gap, or at any rate, a region of lower density, and this suggests very much more exciting possibilities.

Naturally enough this motion of the Galaxy has been analysed in all sorts of ways: all its consequences investigated and the finer details filled in. The difficulty has been to include a sufficient stretch of the whole dimensions in the observations, and there has been a general tendency to use objects visible at very large distances for the analysis of the motion. One of the early studies used the O and B type stars and more recent ones have used the globular clusters and the planetary nebulæ.

The importance of these studies is that, if a body is being

Fig. 43. STAR STREAMING AND GALACTIC ROTATION



It is difficult to fit both of these into the same picture. One way of doing this is illustrated in the diagram. The cross represents the position of the sun, a considerable way from the galactic centre. If the stars are moving in long thin orbits round the centre, those passing near the sun will always be either on the outward or homeward leg of the course, and so will have an apparent preference for motion towards or away from the centre. If all are going round the centre anticlockwise, the galaxy as a whole will show rotation in that direction.

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held in an orbit then there must be a certain amount of matter inside the orbit to provide the necessary attraction. That means that by studying the motion at different distances from the centre we can estimate how much matter there is interior to each distance. This has been done, and it turns out that the whole Galaxy has a mass of something like 200,000 million suns, rather more than half being concentrated near the centre. This is not to say that the Galaxy contains 200,000 million stars like our sun, for an unknown amount, possibly even the major part, is in the gas and dust clouds; besides the local aggregations like the Orion nebula there are very much more tenuous general clouds of gas which contain only something like one atom per cubic yard, against 27 million million million molecules per cubic centimetre for ordinary air, but the volume is so enormous that if the whole Galaxy contained a gas cloud of this density it would use up about a million suns. What is most surprising of all is that these gas clouds are rotating too. There is no question of so tenuous a gas being dragged round by the movement of the stars. Even in a

very dense gas the disturbance produced by a ball moving through it only extends for a few diameters. Nevertheless, the gas is rotating and at roughly the same rate as the star system.

We have spoken of the large scale motion of big groups of stars. There is however a small-scale motion too. The motions of the stars within the group near the sun are not random. They show a sort of preference for moving towards or away from the sun. This 'star streaming' as it is called is not a compulsion, but rather a decided preference, of the same kind that is seen half a mile away from a football ground just before a match. Casual passers-by go about their business in all directions, but on the whole there is a flow in a particular direction. This is the phenomenon of star streaming and it may be that it is to be combined and reconciled with the rotary motion in the following way: if one supposed that all the stars were going the same way round the centre, just as the planets do round the sun, then, near the edge of the system, we might have stars travelling in all directions on all sorts of orbits as shown in figure 43. However a good many of the stars would be on the outward or homeward stretches of their orbits, and rather few on the turn-round part. They would have a preference for the in or out direction, and in addition the whole system would be turning. The author does not put this forward as a statement of what is happening or indeed as a summary of what is generally held to be true. It is merely one way in which the pictures *might* be combined. If this were the true state of affairs it would be difficult to detect directly. A century of exact observation at most does not bring a large portion of a 250 million year orbit under view.

So much for own Galaxy, but as we have already admitted, there are millions more constructed roughly according to the same pattern. At one time it was thought that our Galaxy was a particularly large specimen, but the reduction in estimates of its size, and the discovery that other Galaxies are more extensive than was first thought, brings us to the present position when our Galaxy is regarded as large, but not so large as to be in a different class from the general run.

Fig. 44. PLAN OF LOCAL CLUSTER

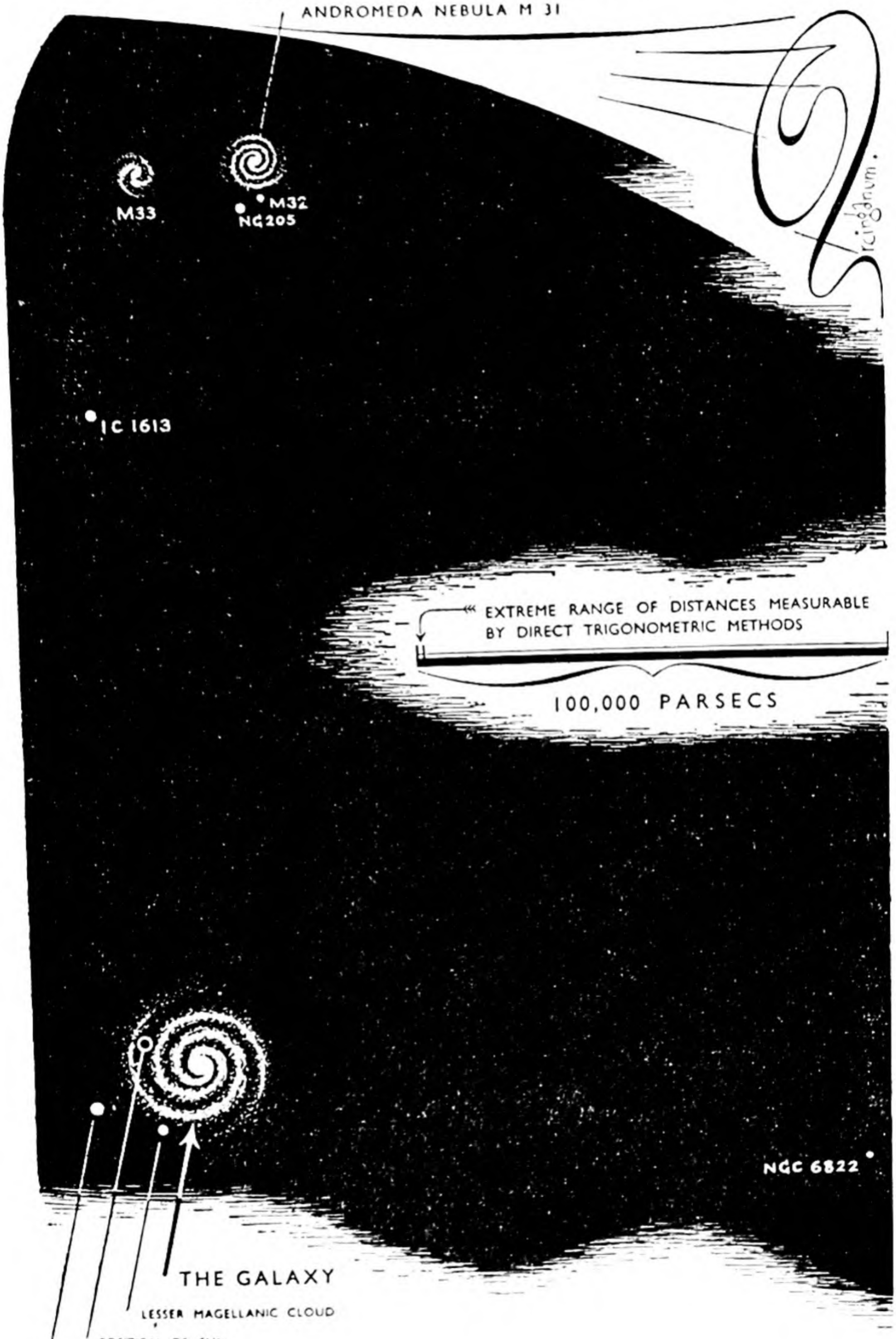


TABLE VII

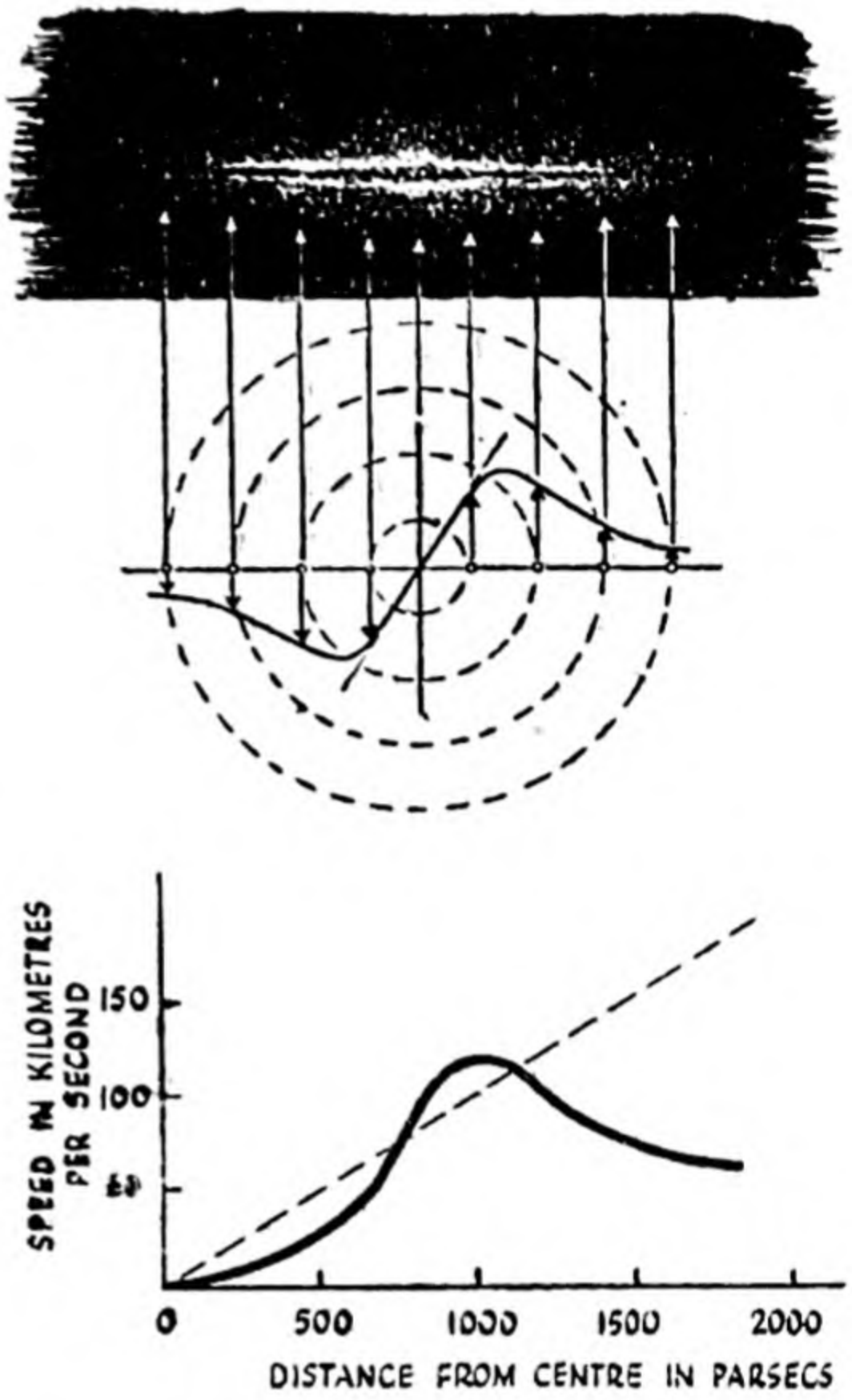
THE LOCAL CLUSTER OF NEBULÆ

	Distance (Parsecs)	*Dimensions*
Lesser Magellanic Cloud	29,000	1,800 (diameter)
Greater Magellanic Cloud	26,000	3,400 ,,
M 31 (The Andromeda Nebula) (spiral)	210,000	12,000 ,, nucleus 900
M 32 (satellite system of M 31) (elliptical)	3,700 nearer than M 31	500
NGC 205 (elliptical)	9,200 nearer than M 31	750
M 33 (Open spiral in constellation Triangulum)	220,000	3,700
NGC 6822 (irregular)	164,000	1,000 × 500 core 400 × 140
IC 1613 (irregular)	280,000	1,300
The Galaxy (? spiral)	—	30,000 diameter

These Galaxies, about four million in number in the part of space accessible with modern telescopes, appear to be scattered fairly uniformly throughout space with an average distance between them of round about a quarter of a million parsecs. There are however clusters of nebulæ, and our own Galaxy is a member of such a cluster of about a dozen. The members of this local cluster are illustrated in figure 44 and described in the table. Two of these are the Magellanic Clouds, visible to the naked eye in southern latitudes as dimly luminous areas about a degree across. They are rather small and appear so large only because they are comparatively near to us at distances of about 30,000 parsecs. The next fully-fledged Galaxy in our cluster is the Andromeda nebula visible to the naked eye on moonlight nights as a very disappointing sight by comparison with the magnificent photographs obtainable in modern long-exposure instruments. All that is visible to the naked eye is the central nucleus or condensation and even in the best photographs its details are hardly shown as far out from the centre as the corresponding distance of our sun from the centre of our Galaxy.

In many ways the Andromeda nebula may be regarded as a twin of our own Galaxy. It is rotating and the rotation is of the same kind as that seen in our own Galaxy. This cannot be discovered by watching for changes in position. It is

Fig. 45. *THE ROTATION OF NEBULAE*



The great nebulae are rotating in a way similar to the rotation of the Galaxy. Observations of the speed of approach or recession of different parts of a nebula (shown schematically in plan below) show that the right-hand side is receding, the left approaching. The arrows represent these speeds, and a graph drawn through the arrow heads shows the relation between the speed and distance from the centre. If the nebula were turning like a solid wheel the graph would be a straight line. Near the centre it is a straight line, but the outer parts lag behind. The lower curve shows the actual velocities observed in the case of the nebula M33.

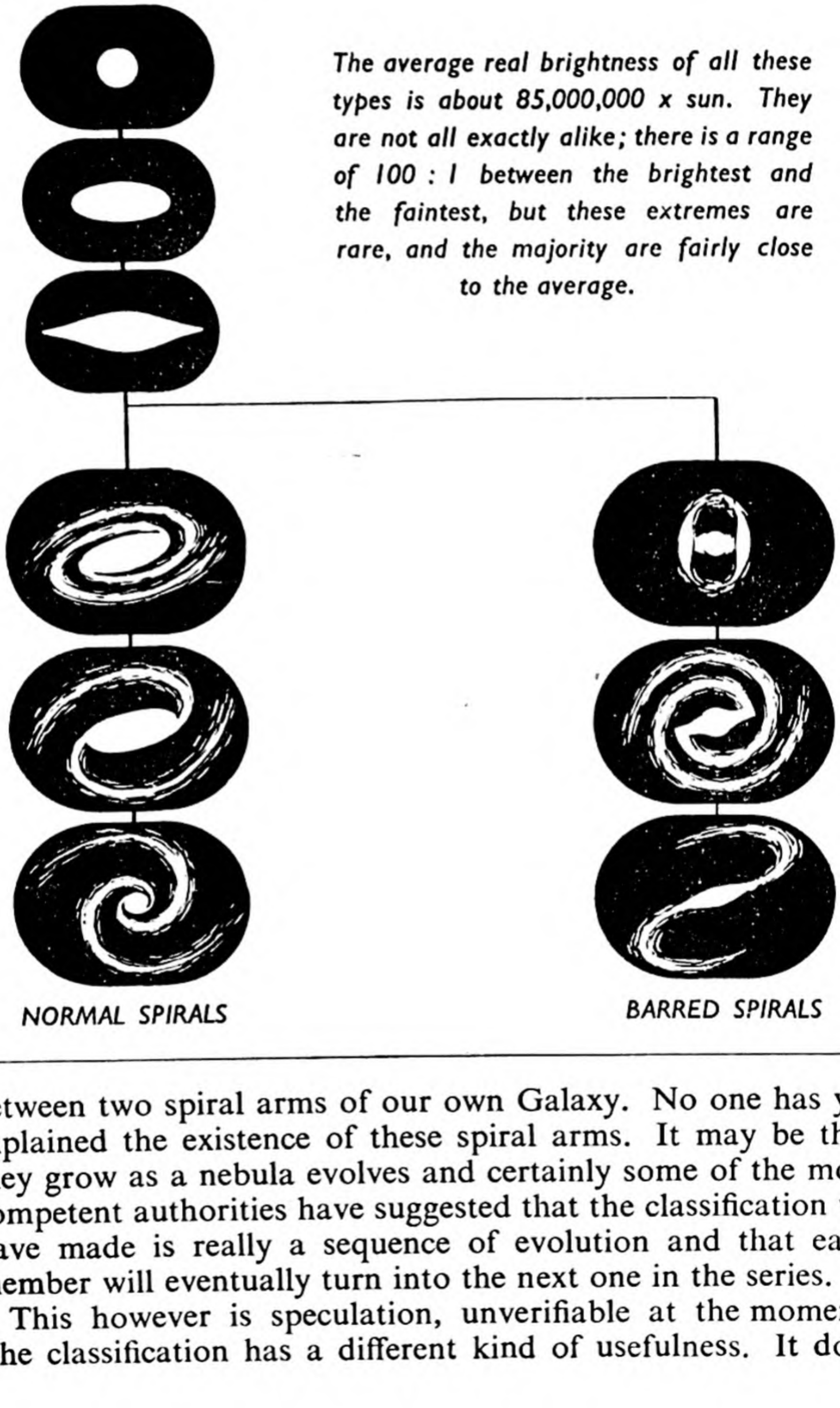
discovered spectroscopically, the line displacements due to the Doppler effect showing the speeds towards or away from us of various features, and these speeds are determined in miles per second (Fig. 45). The Andromeda nebula contains globular clusters, irregular clusters, and gas clouds. Cepheid variables and novæ have been observed in it and their rate of variation and maximum apparent brightness respectively have given us checks on the distance of the nebula. The Andromeda nebula is typical of many in this, and it is one of the most useful facts about super-novæ that they turn up even in the most distant Galaxies and at their maximum brightness give out about as much light as the nebula itself. It follows therefore that supernovæ will give us a means of estimating distances as far off into space as we can observe, for at very large distances we have to deal only with Galaxies and not with individual stars.

One of the difficulties about photographs of nebulæ is that they constitute an observation from a fixed point. We are tied to the earth; we cannot move round a nebula to take a look at it. We cannot usually find out which edge of the nebula is nearest: we cannot tell whether we are looking at it 'from the top down' or 'from the bottom upwards'. Every photograph looks as if the view is an 'on-top' one, but it continues to look the same even when we turn the picture upside down. However, recently observations of the Andromeda nebula have shown that the stars of one edge are redder than those of the opposite edge, which means that the former stars are seen through some of the gas clouds associated with the nebula and that it is therefore presumably the more distant one.

Even more serious is the fact that we cannot be certain of the true shape of a nebula. Is the Andromeda nebula circular in plan and is our position such that we have a three-quarter face view of it, or is it elliptical? It seems most probable that it really is circular for in a tour round the sky we find many objects which look very like the Andromeda nebula seen from a variety of angles. Our general notion of the universe is that of a collection of nebulæ circular in plan tilted up in all directions just as the orbital planes of binary stars are tilted in all directions—some being seen in plan, others edge on and others three-quarter face.

The first step in each new science is to find a system of classification, and even a cursory study of nebular photographs shows that we have to deal with a variety of objects. They have been separated into classes, ranging from the almost spherical globes of light which show practically no detail at all, through a more flattened shape to a lens-shaped type, and then to a more open type in which the structure is more palpably broken up into stars. A characteristic of this type of nebula is the existence of pairs of spiral arms which give it a catherine-wheel appearance (Fig. 46). Such arms may be present in our own Galaxy, but we find it as difficult to observe them as we should if asked to decipher the inscription on a coin by looking at its edge. It has, however, been suggested that the discovery that the sun is in a region where stars are comparatively scarce may be explained by supposing that the sun is

Fig. 46. TYPES OF NEBULAE


ELLIPTICAL NEBULAE
The average real brightness of all these types is about 85,000,000 x sun. They are not all exactly alike; there is a range of 100 : 1 between the brightest and the faintest, but these extremes are rare, and the majority are fairly close to the average.
NORMAL SPIRALS
BARRED SPIRALS

between two spiral arms of our own Galaxy. No one has yet explained the existence of these spiral arms. It may be that they grow as a nebula evolves and certainly some of the most competent authorities have suggested that the classification we have made is really a sequence of evolution and that each member will eventually turn into the next one in the series.

This however is speculation, unverifiable at the moment. The classification has a different kind of usefulness. It does

appear that each type is a more or less standard article constructed to roughly the same pattern and having roughly the same brightness. This means then that faintness or brightness is due to difference of distance alone, and it also means that when we have reached out into space to distances where individual stars such as Cepheids cannot be distinguished, then we still have a chance of estimating distances, which may be checked if we should ever be lucky enough to pick a nebula containing a supernova. The chance of this happening is however small, as can be seen by setting the few dozen supernovæ which have been observed against the millions of known nebulæ. In fact the only reliable routine method of estimating the distances of very remote nebulæ is by assigning them to a certain type—which can be done on shape alone—and then using the previously determined real brightness for this type.

Nebular research is now passing out of this botany stage of classification. The studies of the rotation of some of the nearer nebulæ were published in America in 1940, but in one respect this type of work had already advanced very far. This branch of study is concerned with the motions of the nebulæ.

In most nebulæ two spectral lines due to calcium are prominent and their displacement can be used to determine the speed of approach or recession of the nebula in which they are observed. When these speeds are measured in a large number of nebulæ it is found that there is a quite definite relation between the speed of recession and the distance. The further off a nebula is, the faster it is moving away from us. On the average, for each million parsecs of distance there is a speed of recession of 550 kilometres per second.

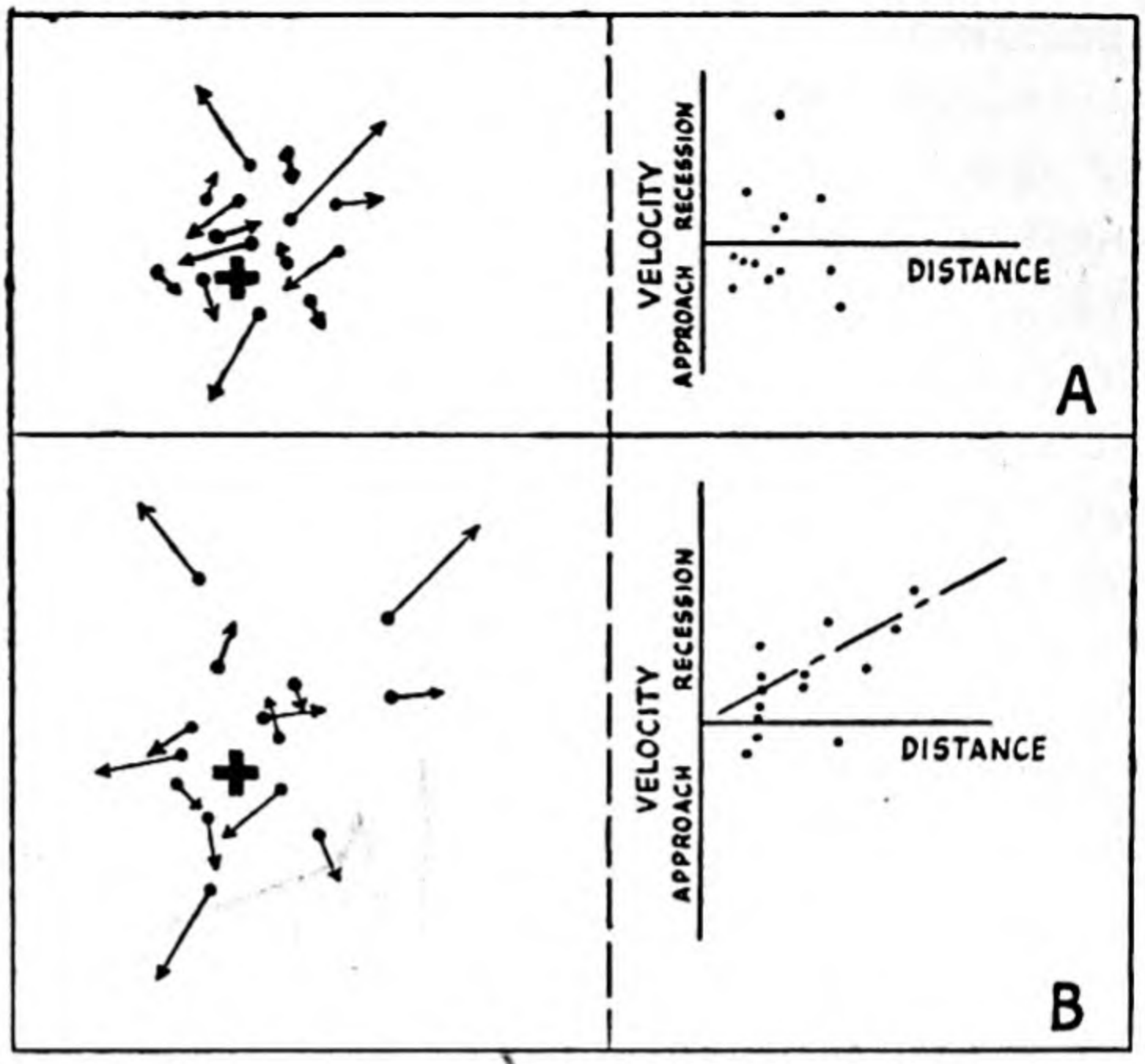
Once this relation has been established it may be used for estimating distances on the assumption that it holds for all distances. The implications of this relationship are worth considering in more detail. At first it looks as if we are in a favoured position in the universe; that we are at the centre and that all matter is running away from us. Even here, however, we can find no privilege for ourselves, who were once the centre of all creation. It appears that for some reason a general spreading out of the matter in space is taking place and it can easily be shown that from any other point in the universe an observer would see the nebulæ moving

away from him, the more distant having the greater speeds of recession.

The interpretation of this velocity-distance relationship is not so much a matter for the astronomer as for the student of cosmological theory such as the later developments of general relativity. A variety of interpretations has been put on it. In the first place there is doubt whether the red-shifts are to be interpreted as due to velocity at all. There is some reason for thinking that light in passing over very great distances may become reddened in process of time. Curiously enough it is a view of this kind which is held by Hubble of Mount Wilson, the foremost nebular astronomer of to-day and the man who put the velocity distance relationship on a firm foundation. The chief reason why such spectral shifts are thought to be due to some other cause than a velocity is that the velocities are extremely high. If velocity is the true cause, then distances have already been reached at which the velocity of recession is over ten per cent of that of light. Any approach to a velocity comparable with that of light causes a good deal of hard thinking, for it is known that no material body can move so fast as light, and that as the velocity approaches that of light a number of curious phenomena such as change in mass, begin to exhibit themselves.

A second interpretation due to Professor E. A. Milne starts from the straightforward idea that they are to be interpreted as velocities, in which case the appearance of the velocity distance relationship is a quite natural consequence. If we suppose that in the past all the nebulæ were crowded together in a comparatively small region of space, and that they had their present velocities, then, as time passed the whole swarm would become dispersed. Those moving inwards towards the centre of the mass might be expected to cross right through the swarm and emerge on the other side. As the dispersion proceeded the greatest distance would have been covered by those moving fastest, so that eventually there would be a sorting out of the whole swarm, with the fastest moving ones at the greatest distances (Fig. 47). Starting from this type of conception Professor Milne has developed a theory of relativity based on a careful investigation of the exact type of knowledge which it is possible to obtain through obser-

Fig. 47. THE VELOCITY DISTANCE RELATION



The more distant nebulae are receding the fastest. This is not a rule which is imposed, it can arise naturally. If all the nebulae are close together in space as in A and are moving at random, there will be no relation between distance and speed. After the lapse of time, when the nebulae have all moved to the points of the arrows shown in A, diagram B will hold. The fastest moving nebulae will have gone farthest, and a rough relation between distance and speed is beginning to appear. The positions and speeds in these two diagrams were chosen at random, and the graphs are deduced from these chance distributions.

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vations of nature and has arrived at a theory of a universe which behaves like the one which we observe and which is such that every observer feels himself to be at its centre and sees all the nebulæ apparently running away from him. There is a limit to his range of observation—a sort of horizon—at which new mass is appearing within his purview. A second consequence is that if the history of the universe is traced backwards it becomes necessary to use two sorts of time-scale in one of which an infinite period has elapsed whereas in the other a finite period has passed. It turns out that the infinite time scale is the natural one which is, as it were, determined by the sort of universe which it is describing, so that we need not think of any initial epoch, any beginning act of creation which is necessary to set the whole system into action.

Yet another view is based on the orthodox theory of relativity first propounded by Einstein. Einstein's universe was at first a purely static affair but it was found that it was unstable: that the slightest disturbance would produce an expansion.

This expansion would be reflected in the behaviour of the matter contained in the universe, which would tend to spread out and become more dispersed. Sir Arthur Eddington was the chief protagonist of a development of this view and he considered that at any time the behaviour of atoms must reflect the condition of the whole of the universe. He attempted to find relations between the constants describing the behaviour of atoms and those describing the behaviour of the whole universe. He considered that it was possible for example to calculate the rate at which nebulæ would recede from the atomic constants, and he had obtained a value fairly close to the observed one.

It is hardly to be hoped that these sketches will give any real clue to the present state of the cosmological theory. There appear to be certain contradictions between the views advanced, and it is hardly our place as interpreter to attempt to give judgement. We must try to hold the ring while the giants battle. We make the attempt at giving some indication of the divergent views because an impression is often given that those matters are settled. They are not. They are still the subject of controversy and will remain so for some time to come. The theories are all difficult and it is almost impossible for any but the professional who has specialized in this branch to the exclusion of all else to appreciate the points at issue and to endeavour to give any kind of judgement. It must however be emphasized that these complications are not indulged in by their authors just for intellectual amusement. There are very real difficulties to be overcome. All our simple ideas would lead us to suppose that matter, left to itself would tend to coagulate and cohere, whereas we find the opposite to be true, at least if we take the red-shifts at their face value. Some new step must be taken and these theories are a variety of essays at making that step. It may be that they are less inconsistent than they appear at first sight. Cases are known in the history of science where two apparently antagonistic theories have been found in the end to be alternative ways of saying the same thing.

The fact remains that two large pieces of theory have to be built up. One is a general theory which will cover the recession of masses at large distances while the other is the combina-

tion of relativity theory with the theory of the behaviour of the atom. Relativity theory requires that all laws of physics should be so framed that they may be stated in the same way for all observers—however they are moving, in whatever gravitational field they find themselves. The present theory of the atom cannot be so expressed, and search is being made for a theory which will either give the same results as those observed in connection with atomic behaviour or ones so near as not to have been distinguished from them so far, and which will also generalize in the way required by the relativity theory.

Chapter Nine

TAILPIECE

IT has become customary to end books on popular astronomy with a chapter dealing with the philosophical implications of the subject, and emphasizing the essential mystery of the universe. As we have said already this is not a treatise on philosophy, and we take the view that such a chapter would be somewhat out of place in a book intended to give an impression of the way in which astronomers conduct their work. In their ordinary investigations astronomers are rarely concerned either with the extreme depths of space or with anything but the exact recording of observations and the development of a theory to cover and explain those observations. Philosophy, other than the working rules of the scientific method has little or no relevance to that work.

It is also most unfortunate that an impression should be given—as, presumably unintentionally, it has been given—that because the ideas involved in the more abstract developments of astronomy are difficult to grasp, then there is necessarily something mysterious and imprecise about them. Surely the most striking thing about the universe is not its mystery, but that so much progress can be made in explaining it by means of precise notions based in the end on the behaviour of atoms in laboratories on the earth. There is nothing mysterious about the behaviour of an atom at the other end of the universe. If you could go there the atoms would, so we assume, look precisely the same as those found here. Perhaps even, looking back, we might get a momentary mystical thrill from the contemplation of a mysterious oversize Galaxy containing a dwarf star round which are moving a few specks of solid matter. The command over natural forces and the understanding of nature is to be obtained just as much in our own familiar surroundings as it is in contemplation of the very distant.

For us, the importance of knowing about the farthest depths of space is that we thereby remove mysteries. In the past man

was beset by fear of the unknown. His life was at the mercy of evil spirits who trundled the sun and planets about the heavens: who brought famine, drought, and flood on an erring humanity. If there is a lesson to be learned surely it is the lesson of emancipation from these old fears: the lesson that the stars do not influence our lives and that any one who says so is probably actuated by some sinister motive of his own which makes it advantageous for him to deceive his fellow creatures. If by mysterious, we mean not fully known, then indeed the universe is mysterious, but we learn from the past that the mystery is not insoluble and that, in the end, the ignorance which clogs man's progress can and will be cleared away.

To speak thus in connection with astronomy may seem a little far fetched, but it may help us to guess a little at the future. It seems that we have now reached a stage in astrophysics, where the stars may be regarded as experiments set up for us and proceeding inevitably on their way. We are beginning to be able to interpret the results of those experiments, and it is perhaps not too rash to expect that the debt incurred by astronomy to physics when first the atomic theory was applied to stellar behaviour, will begin to be repaid with a new system of knowledge of the behaviour of hot gases at very high temperatures. This knowledge though gained from the stars will be universal and will be laid up, ready for use in a host of applications, perhaps in connection with other sciences, perhaps even in connection with industry.

More generally we are clearly due for a great synthetic theory which will bring together general physics enshrined in its relativity dress with the physics of the atom. The budding of many theories relating the two which we have mentioned in the last chapter indicates that a check has been reached and the research workers are casting about for a new line of advance. When it has been found, it will probably have that characteristic of all great theories—essential simplicity. It will unify what now seems to be diverse and it will find a single clear road through seemingly unrelated phenomena. The various theories are attempts to fit the jigsaw together. The whole matter will bear a simpler and more readily understandable aspect when the whole pattern has been fitted into place. A new stage of progress will have been reached, and will continue.

GLOSSARY

ABERRATION (of lenses or mirrors): Defects of image formation.
ABSOLUTE MAGNITUDE: the real brightness of a star, etc.
ABSOLUTE TEMPERATURE, Kelvin temperature: temperature measured on a scale beginning at absolute zero (−273° C.) and having degrees of the same size as the Centigrade scale. Temperatures denoted by ° K.
ABSOLUTE ZERO: the lowest temperature: Temperature at which all energy has been extracted from a body (−273° C.).
ÅNGSTROM UNIT: One hundred millionth (10^{-8}) of a centimetre. Unit used in measuring wavelengths of light.
APPARENT MAGNITUDE: Apparent brightness of a star, etc. Depends both on distance and real brightness (absolute magnitude).
ASTEROID: Alternative name for minor planet.
ASTRONOMICAL UNIT: Average distance of earth from sun = 93,005,000 miles.
ASTROPHYSICS: Application of physical laws to study of constitution, etc. of stars.
BINARY STAR: A pair of stars moving in orbits round one another under their mutual gravitational attraction.
BLACK BODY: A body which absorbs all radiation falling on its surface.
BOLOMETRIC MAGNITUDE: Magnitude of a star based on total radiation emitted including invisible radiation.
CASSEGRAIN REFLECTOR: A reflecting telescope employing a convex secondary mirror to return the light beam through a central hole in the main mirror.
CENTRIFUGAL FORCE: The force which must be applied to keep a body moving in a curved path.
CEPHEID VARIABLE: A type of star whose light is variable, the variation being of a characteristic type. After the prototype δ Cephei.
CLUSTER: A group of stars.
CORONA: A tenuous gas cloud of a pearly-white colour enveloping the sun and extending for a million miles or more.

Visible only during a total solar eclipse except with special instrumental equipment invented by B. Lyot.

DAY: Period of rotation of earth on its axis. *Sidereal day*: rotation period as judged by apparent movement of stars = 23 hours 56 minutes mean solar time.

DECLINATION: A system resembling latitude and longitude is used by astronomers for marking positions on the sky. Declination corresponds to latitude: sidereal hour angle (R.A.F. parlance) or right ascension (astronomical parlance) are two ways of specifying the angle corresponding to longitude.

DIAMETER, ANGULAR: Angle between lines from observer's eye to opposite edges of an object; apparent size of an object.

DIFFRACTION GRATING: A device for producing spectra consisting of a very large number of closely ruled parallel lines scratched on a sheet of glass or metal.

DISPERSION: The spreading out of light into a spectrum.

DISTANCE, ANGULAR: see Diameter, Angular.

DOPPLER EFFECT: Rise or fall in pitch of note when source of sound is approaching or receding. Blue or red shift of spectrum lines when light source is approaching or receding.

DWARF STAR: Stars of later spectral type (lower temperatures) fall into two groups according to brightness, diameter, and mass, the groups being called giants and dwarfs.

ECLIPSING BINARY: Binary star in which stars pass in front of each other in their orbital rotation and interrupt each other's light.

ECLIPTIC: The plane of movement of the earth round the sun; seen from the earth as an imaginary line encircling the sky. All the planets, moon, and sun move nearly in this line.

EFFECTIVE TEMPERATURE: The effective temperature of a star is the temperature of a black body emitting the same total radiation per unit area as the star does.

EINSTEIN SHIFT: Red shift of spectrum lines in stars with large force of gravity.

ELECTRO-MAGNETIC RADIATION: Light waves, radio waves, infra-red rays, X-rays, ultra-violet rays are included under this general name.

ELECTRON: Elementary particle of negative electricity, having mass of 1/1840 of proton.

EQUATOR: Of earth, planet, sun, etc. Plane in which earth, etc. is turning.

EROS: Minor planet approaching to within 15,000,000 miles of the earth every 30 years.

EXTRA-GALACTIC NEBULA: A group or system of stars having a cloud-like appearance in a small telescope, and of a real size about the same as that of the Milky Way or Galaxy. So-called to distinguish it from the word nebula as used to describe a gas cloud forming a minor feature of the Galaxy.

EYE-PIECE: The part of a telescope through which the observer looks.

FACULÆ: A cloud of hydrogen above the sun's surface.

FLOCCULI: A cloud of calcium vapour above the sun's surface.

FLARE, SOLAR: Outburst of radiation from small region of sun's surface.

FOCAL LENGTH: Distance behind a lens at which the image of a distant object is formed.

FOCUS, FOCAL PLANE: Position of formation of optical image.

GALACTIC NEBULA: Small gas or dust cloud within the Galaxy (see extra-galactic nebula).

GALAXY: The Milky Way; the group of stars, of which the sun is one, which are seen as the Milky Way.

GIANT STAR: See dwarf star.

GRATING: see diffraction grating.

HELIUM: The second lightest chemical element first discovered spectroscopically in the sun.

HYDROGEN: The lightest chemical element and the main constituent of stars.

INTERFERENCE OF LIGHT: Phenomenon of interaction of light waves coming from same source by two different routes. Addition of such waves results sometimes in mutual cancellation producing darkness.

INTERFEROMETER: Instrument for measuring wavelengths of light. *Stellar interferometer*, instrument for measuring separation of stars or angular diameters of stars.

IONIZATION: Removal of one or more electrons from an atom. *Ion*, an atom which has been ionized.

ISLAND UNIVERSE: Name applied sometimes to extra-galactic nebula.

LATITUDE: Angular distance north or south of equator of earth, sun, planet, etc.

LIGHT CURVE: Graph showing way in which brightness of variable star, nova, etc. varies with time.

LIGHT-YEAR: Distance travelled by light-wave in one year = 3·25 parsecs.

MAGNITUDE: Number describing brightness (apparent or absolute) of a star, planet, etc.

MASS-LUMINOSITY RELATION: Relationship found to exist between mass and real brightness of stars.

MEAN: Average.

MERIDIAN OF OBSERVER: Imaginary line drawn on sky through the zenith and the south point of the horizon.

METEOR (Shooting Star): Small particle of matter rendered luminous on entering earth's atmosphere.

MILKY WAY: See Galaxy.

MINOR PLANET: One of group of small planets between orbits of Mars and Jupiter.

MOVING CLUSTER: A group of stars moving together through space.

NEBULA: See extra-galactic nebula, galactic nebula.

NEWTONIAN REFLECTOR: Reflecting telescope employing small secondary mirror or prism to form image at the side of the tube.

NOVA: Star whose light undergoes sudden increase accompanied by violent ejection of matter from surface.

NUCLEUS: The central, heavy, positively charged, part of an atom.

OBJECT GLASS, OBJECTIVE: The main lens or mirror of a telescope.

ORBIT, (of Planet, Star, Electron): Path round, sun, companion star, nucleus.

PARALLAX, STELLAR: Angular length of radius of earth's orbit as seen from star.

PARSEC: Distance of star with parallax of $1'' = 206{,}265$ astronomical units.

PERIOD (of Planet, Variable Star, etc.): Time to make complete circuit round sun, to complete one cycle of variation.

PERIOD-LUMINOSITY LAW: Relation found to exist between period of Cepheid variable star and its real brightness.
PHASES: Partial illumination of visible disc of moon or planet.
PHOTOMETER: A light-measuring instrument.
PLANET: Small solid body having no light or heat of its own which moves round sun.
POLE (of Earth, Planet, Sun): Point where axis of rotation cuts surface of earth, etc.
PROMINENCE: Flame-like cloud of luminous gas above sun's surface.
PROPER MOTION: Change of position of star in sky due to its own motion through space.
PROTON: Nucleus of hydrogen atom.
QUANTUM THEORY: Physical theory of interaction of radiation and matter.
RADIAL VELOCITY: Velocity of star directly towards or away from observer; line of sight velocity.
RADIATION: Light, including invisible light; electro-magnetic waves.
RAY: Line along which light waves travel.
REFLECTOR: Telescope using curved mirror to bring rays to a focus.
REFRACTOR: Telescope using lens to bring rays to a focus.
RESOLVING POWER: Capacity of telescope or other optical instrument for producing distinct images of objects separated by only a small angular distance.
RETROGRADE MOTION: Motion opposite to the general direction of movement of the planets and satellites.
RIGHT ASCENSION: See Declination.
SATELLITE: A moon.
SHIFT (of Spectrum Lines): Displacement of spectrum line from the true position by Doppler effect, Einstein effect, etc.
SHOOTING STAR: See Meteor.
SIDEREAL HOUR ANGLE (S.H.A.): See Declination.
SLIT: Narrow aperture with parallel edges through which light is admitted to spectroscope.
SPECTRUM: Band of light from star, sun, etc. in which each position corresponds to a definite wavelength, produced by spectroscope.

SPECTRUM LINE: Line crossing spectrum at right-angles representing excess or defect of radiation of particular wavelength and producing bright (emission) or dark (absorption) line.

SPECTROSCOPE: Instrument for analysing light into constituent colours.

SPECTRAL TYPE: Classification of star according to appearance of spectrum or according to colour.

SPECTROSCOPIC BINARY: Binary star detected by presence of two spectra superimposed.

STAR: Luminous, approximately spherical mass of hot gas.

STAR STREAMING: Group motion of stars superposed on irregular random motion; preference of stars for movement in a particular direction.

SUN-SPOT: Disturbed area of lower temperature than rest of sun's disc appearing dark by contrast.

TRANSIT: Passage of inner planet in front of sun's disc.

TRANSVERSE VELOCITY: Speed of star across line of sight; part of stellar movement producing proper motion.

VARIABLE STAR: One whose brightness varies or appears to vary.

WAVE: A regular variation in time and space.

WAVELENGTH: The distance between crests of a system of waves.

WHITE DWARF: A type of faint star of high temperature having a very high density and a very small radius.

X-RAYS: Electro-magnetic radiation of very short wavelength.

ZENITH: The point of the sky directly overhead.

ZODIAC: The zone of the sky including the ecliptic.

ZODIACAL LIGHT: A faint glow of light due to scattering of sunlight from a dust cloud within the solar system.

READING LIST

STAR GUIDES AND ELEMENTS OF POSITIONAL ASTRONOMY

First Steps in Astronomy: P. F. Burns. Gunn & Co.

Signpost to the Stars: F. E. Butler. George Philip & Son, Ltd.

Elementary Astronomy: E. A. Beet. Cambridge University Press.

ELEMENTS OF NAVIGATION

Astrographics: Frank Debenham, Heffer & Sons, Ltd.

STAR ATLAS

Norton's Star Atlas: Gall & Inglis.

HISTORICAL

Greek Astronomy: Sir T. L. Heath. Dent & Sons, Ltd.

Mathematics for the Million: L. Hogben. Allen & Unwin.

Science for the Citizen: L. Hogben: Allen & Unwin.

Astronomical Discovery: H. H. Turner. Arnold.

History of Astronomy in the 19th Century: A. M. Clerke. A. & C. Black.

The Royal Observatory at Greenwich: H. Spencer Jones.

GENERAL ELEMENTARY TEXTS

General Astronomy: H. Spencer Jones. Arnold.

From Atoms to Stars: Martin Davidson. Hutchinson.

The Sun the Stars and the Universe: W. M. Smart. Longmans

Astronomy: H. N. Russell, R. S. Dugan and J. Q. Stewart. Gunn & Co. (2 Vols).

The Universe Around Us: Sir James Jeans. Cambridge University Press.

The Stars in Their Courses: Sir James Jeans. Cambridge University Press.

MATHEMATICAL ASTRONOMY

Elementary Mathematical Astronomy: Barlow and Bryan, revised by H. Spencer Jones. London University Tutorial Press, Ltd.

Spherical Astronomy: W. M. Smart. Cambridge University Press.

Foundations of Astronomy: W. M. Smart. Longmans.

ASTRONOMICAL INSTRUMENTS AND OPTICAL PHENOMENA

The Glass Giant of Palomar: D. O. Woodbury. Heinemann.

Light and Colour in the Open Air: M. Minnaert. Bell.

Amateur Telescope Making: ed. Albert G. Ingalls. Munn & Co., Inc.

THE SUN

The Birth and Death of the Sun: Gamow. Macmillan.

The Sun: G. Abetti. Crosby, Lockwood.

(Advanced) *Eclipses of the Sun and Moon*: C. W. Dyson and R. v. d. R. Woolley. Oxford University Press.

NEBULÆ

The Realm of the Nebulæ: E. Hubble. Oxford University Press.

JOURNALS

The Royal Astronomical Society, Burlington House, Piccadilly, London W.1 publishes:

Monthly Notices and *Memoirs* (new astronomical researches).

Occasional Notes (more popular discussions).

The British Astronomical Association c/o Royal Astronomical Society publishes its journal monthly.

The Observatory Magazine (address: The Editor, Royal Observatory, Greenwich, S.E.10) is a more elementary journal containing general articles, notes, astronomical news, etc.

Discovery and *Nature* (monthly and weekly respectively) contain regular notes on celestial phenomena and occasional astronomical articles.

The Halley Lectures, published subsequently by the Oxford University Press, deal largely with astronomical subjects.

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